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GENERAL MOTORS CORPORATION

# ROVING VEHICLE MOTION CONTROL

FINAL REPORT


Prepared by

B.P. Miller, T.M. Corry, D.E. Johnson,

R.J. Johnston and J.E. Lingerfelt



Prepared for

JET PROPULSION LABORATORY

CALIFORNIA INSTITUTE OF TECHNOLOGY

UNDER JPL CONTRACT NO. 951829

Sponsored by

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

UNDER NASA CONTRACT NAS7-100




AC

Lunar & Planetary Programs

AC ELECTRONICS-DEFENSE RESEARCH LABORATORIES

SANTA BARBARA, CALIFORNIA

## NOTICE

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# ABSTRACT

This report covers a study and analysis of the problem of controlling roving surface vehicles at lunar and planetary distances. The first portion of the report presents the foundations of the study - historical background, nature of the roving vehicle motion control (RVMC) problem, and the operational constraints and ground rules for the study. This is followed by a delineation of missions which were postulated and the terrain models which were assumed. An approach to the analysis of functional requirements is presented, and general system configurations are worked out for each mode of operation.

The various alternatives for subsystem implementation are discussed relative to both the current and projected state of the art, and data are provided for making rough estimates of overall system weight requirements. A separate section of the report is devoted to the human factors involved in RVMC operations. System parameters such as power, antenna gain, information rate, range, data processing time, sensor resolution, etc., are traded off to evaluate their relative significance to the overall problem and to determine order-of-magnitude values for optimum performance measured in terms of average locomotion velocity. Suggestions are offered for the directions in which future analytical effort could most usefully be applied.

It is concluded that on-board decision-making capability is required at planetary distances and that the current state of the art points toward non-image type sensors compatible with relatively simple, rapid data processing for routine control functions. Image sensors will still be needed for path planning functions.

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# 1.0 INTRODUCTION

## 1.1 BACKGROUND OF THE STUDY

As the U.S. Space Program progresses toward the first manned landings on the moon, it is important to consider the directions into which future efforts should be channeled and the associated problems and requirements. Among the diverse possibilities are extended-area unmanned exploration of the moon and planets. For missions of this type, cogent reasons can be given for incorporating the ability to move about by including an instrumented roving vehicle on the landing spacecraft. The feasibility of doing so depends directly upon the ability to control the motions of the roving vehicle both safely and effectively from the earth. To investigate this problem, the Jet Propulsion Laboratory has initiated this study of methods and techniques that might be used to achieve the needed control capability.

There have been previous studies of the problem of remote control of extra-terrestrial roving vehicles. In 1964 and 1965, under the Surveyor Lunar Roving Vehicle Program, both AC Electronics - Defense Research Laboratories (AC-DRL)[1] and Bendix Systems Division[2] contracted with JPL to study the SLRV control problem. These studies, which included experiments with working models and laboratory studies of operator perception capabilities, were tailored mainly to the SLRV mission, i.e., survey and certification of Apollo landing sites on the moon.

In 1961, J.L. Adams,[3] experimentally studied the effects of time lags of up to six seconds in the remote control loops of mobility systems. Chomet, et al,[4] controlled a simple vehicle with time lags of three seconds. In the experiments in these two studies, the time lags were roughly commensurate with lunar distance and the mode of control was basically continuous.

The present study is intended to treat the problem much more generally, by considering the whole range of possible system configurations and techniques applicable to both lunar and planetary roving vehicle motion control, hereafter referred to as RVMC. In addition to analyzing and comparing various possible approaches to the lunar and planetary cases and recommending those system approaches and procedures which show the most promise, the study treats specifically the relative significance of system and subsystem parameters, the effects of constraints imposed by distance, weight, environment, and communication restrictions, and the role of the human in the overall control scheme.

One frequently hears reference to remote roving vehicle motion control in terms of an earth-bound operator grasping a steering wheel or "joy-stick," observing the countryside through the stereo eyes of twin television cameras mounted on the vehicle, and driving much as he would his personal automobile. From the outset, this concept was dismissed as not being a reasonable approach. While the previous studies just cited demonstrated that the human might, in ideal terrain, be capable of dealing with the loop transport delays typical of lunar operation, they do not establish a clear advantage for this type of operation over a step-by-step mode of operation. They do, in fact, point up the problems of disorientation and the stresses imposed on the operator by the anticipation requirements. In addition, the high image frame rates involved are highly wasteful of power and bandwidth, and both the antenna and the cameras would require stabilization. On Mars, the approach seems even less feasible because loop delays may be forty minutes or more and the information rates simply will not permit the luxury of high redundancy inherent in continuous image transmission.

## 1.2 ORGANIZATION OF THIS REPORT

This report is organized along the following lines. The remainder of this introductory section is devoted to an enumeration of the more significant conclusions of the study, a brief discussion of the nature of the remote control problem, and the basic groundrules used to bound the study. This is followed in Section 2 by a discussion of the constraints under which lunar and planetary systems must operate.

A basis for describing roving vehicle missions and terrain environments is next provided, in Section 3. The result of this analysis is a set of three operational modes which are used as a basis for subsequent definition of requirements and candidate system configurations.

A generalized approach to the definition and organization of system functional requirements appears in Section 4, followed by a description of system configurations in Section 5. The means by which systems might be implemented and the state of the art for various alternatives are discussed in Section 6.

Section 7 reviews the three modes of operation from the equipment point of view with emphasis on the relative balance between space-based and ground-based equipment.

Human engineering aspects, including selection, training, and testing of operators, are discussed in Section 8.

A gross parametric tradeoff analysis of the lunar and Martian cases is presented in Section 9, followed in Section 10 by a discussion of some initial thoughts on the subject of mission simulation. Finally, Section 11 treats the question of what additional analysis might be appropriate.

The report has been written so as to constitute an essentially complete documentation of the study itself. Thus, although it has been preceded by two Quarterly Progress Reports, an attempt has been made to integrate the essential parts of those reports into this one. However, in some cases the reader is referred to the Quarterlies for certain detailed information or for consideration of initial thinking which might have undergone modification or evolution as the study progressed.

## 1.3 CONCLUSIONS OF THE STUDY

Necessarily, because of the very nature of the problem and the many unknowns which are not subject to effective analytical treatment, many of the conclusions of the study are tentative. Nevertheless, it is felt that several useful conclusions can be reached regarding the overall approaches which appear promising for RVMC on the moon and planets.

1. Roving vehicle motion control is possible on either the moon or Mars by means of step-by-step (fly-by-wire) control from earth using image sensors augmented with measurement and predictive aids.
2. Use of step-by-step control from earth is highly inefficient for control at planetary distances because of restricted information rates and long transmission lags. It is therefore highly desirable at planetary distances to automate the routine mobility commands using on-board equipment.
3. Image sensors are not currently compatible with such automatic decision processes because they inherently require subtle pattern recognition capabilities not within the present state of the art. Efficient operation of roving vehicles on Mars therefore requires on-board non-imaging sensors capable of providing terrain information in a form suitable for machine evaluation and decision making. This appears to require some development with respect to both the sensors and the data processing approaches but, in the light of the current state of the art, it seems more promising than image processing.

4. Progress of the vehicle will probably be restricted by obscuration of terrain when viewed obliquely by on-board sensors rather than by the inherent range, resolution, or other limitations of the sensors themselves. This will make the development of control strategies very important regardless of the mode of operation.
5. While routine control in automatic modes of operation is likely to be performed with non-imaging sensors, the unique nature of images would still qualify this type of sensor for use in longer-range path planning operations conducted on earth. Since, in this role, image sensors would be used less frequently, and since this function requires much greater precision than routine obstacle detection, the images should be of very high quality even at the price of long readout times.
6. Data rates involved in earth control of lunar vehicles in a step-by-step mode are incompatible with the projected capabilities of the Ground Communication System of the Deep Space Network. Therefore, in this mode of operation, control of lunar vehicles would likely be exercised only through the Goldstone DSIF (Deep Space Instrumentation Facility) Station, thus limiting operations to about ten hours per day. In an automated mode similar to that proposed for planetary control above, control of a lunar vehicle might be accomplished on a round-the-clock basis through overseas DSIF sites.
7. Because of the unusual nature of many of the functions included in RVMC and the unique conditions under which they are performed, it is critical that pre-flight simulation exercises be as realistic as possible.
8. Mechanical aids to routine decision making should be provided to enable human operators to make rapid, error-free decisions and to free them to deal, for the most part, with the unanticipated. These aids might include such devices as photogrammetric aids, rapid recall of past images, a continually updated terrain model, and predetermined reactions to a variety of subsystem parameter anomalies. In the manual, step-by-step or fly-by-wire mode it would also include predictive aids to illustrate the effects of proposed actions.
9. In either lunar or Martian operations, operating windows will frequently impose a serious limitation on overall performance. In order to minimize this limitation, all operations which can be conducted outside of operating window periods should be so scheduled.
10. Except at the greatest ranges, there seems to be little to be gained from the RVMC standpoint by increasing power or antenna gain beyond a certain point.

This point depends upon other factors, but occurs when the time associated with data readout ceases to be a dominant factor in overall control cycle time. Increased antenna gain may actually be a detriment if the improvement in bit rate is offset by an increase in antenna orientation time, since antenna orientation must be accomplished each time transmission of data is required.

11. In determining safe step distances, stereo precision in short-range obstacle detection and avoidance operations is not nearly as important as the range at which obstacles may be detected. When a significant fraction of the surrounding terrain is obscured, the main role of stereo images will be to provide an operator with a sense of three-dimensionality rather than to act as a direct measurement device. Since this is possible with sensors of moderate quality it might give rise to a dual-quality image sensing system where the lower quality images are used for routine hazard detection and the higher quality for path planning and scientific purposes.
12. Data compression has little to offer in the RVMC situation except at the greatest Martian ranges, where a compression factor of even two or three would provide substantial improvement in performance.

## 1.4 NATURE OF THE RVMC PROBLEM

### 1.4.1 Effect of Control Distance

The complexity and difficulty of controlling a vehicle are closely associated with the distance between the vehicle and the controller. Several distinct levels of difficulty may be associated with orders of magnitude of this distance. These levels of difficulty are tabulated in summary form as technical problems in Table 1-1.

a. Operator Alongside Vehicle

An operator walking alongside a controlled vehicle can decide, by direct observation, upon a path leading to the safe achievement of a desired objective. The major control problem is that of incorporating sufficient performance in the vehicle to enable the desired motion to be accomplished. This implies adequate vehicle mobility, fineness of control actions, and predictability of the results of control actions. Sensory capability is through the operator. Command channel requirements are minimal; it is only necessary that an experienced operator have a means of communicating the appropriate locomotion commands to the vehicle. This can be accomplished using control buttons or levers on the vehicle itself, by a mechanical cable connection (as with tethered

Table 1-1
INCREASING CONTROL COMPLEXITY WITH DISTANCE

| | Approximate Distance to Vehicle | Problems |
|---|---|---|
| On Earth | Alongside to approx. 40 meters | Vehicle mobility performance<br>Command and actuation precision |
| On Earth | Approx. 40 meters to 40 km | The above plus:<br>Sensor performance<br>Transmission of sensor data<br>Information display |
| On Earth | Approx. 40 km to 40,000 km | The above plus:<br>Power, bandwidth, information rate tradeoffs<br>Relay links |
| Lunar | 400,000 km | The above plus:<br>Transmission lags (seconds)<br>Earth rotation<br>Unknown environment<br>Payload restrictions<br>Spreading losses |
| Planetary | $40 \times 10^6$ to $400 \times 10^6$ km | The above plus:<br>Transmission lags (minutes)<br>Relative motion of earth and planet<br>Greater spreading losses |

model aircraft), with electrical cables connected between the vehicle and a control box, or with a relatively simple radio link. None of these approaches presents any great difficulty and, in fact, all have been used with considerable success.

b. Distances to a Few Kilometers

If the vehicle is moved, say, a few kilometers from the controller, a new problem arises: the need to sense the immediate environment of the vehicle, and to transmit these data to the controller. A sensor of some sort is needed on the vehicle. The problem of transmitting sensor data introduces a new level of difficulty. The sensor performance may be inferior to that of direct human observation with respect to factors such as resolution, depth perception, color discrimination, and other factors. (It may also be superior from the standpoints of measurement capability and recall.) A means of transmitting the images, e.g., radio, is required and this data link contributes noise, distortion, and bandwidth limiting to the information delivered to the operator. The operator's display device has limited fidelity and light intensity far below that of the original scene. Thus the perception and evaluation capability of the operator is much reduced by the sensor-radio-display chain. In contrast, the command channel and control actuator aspects are not seriously affected. Remote control at these distances is generally possible using continuous, real-time visual imaging. Although this approach may be costly in terms of power or bandwidth, these resources are usually not at a premium and pictures of adequate quality can usually be transmitted at a sufficient frame rate to make this approach feasible.

c. Distances of Hundreds of Kilometers

As the distance between the vehicle and the controller is increased still further to, say, hundreds or thousands of kilometers, one is increasingly concerned about power and bandwidth considerations in the sensor-radio-display chain. Tradeoffs between frame rate, resolution, and field of view on the one hand, and power and bandwidth on the other, may have to be examined carefully. Another new factor shows up at these ranges, since the operator and vehicle may be well beyond line-of-sight to each other. In this case, the design must consider the alternatives of either (1) wire circuits or low-radio-frequency operation, with their problems of bandwidth restriction and interference, or (2) the use of communication relay procedures. The latter may take the form of land-based receiver-transmitter stations, or, if the distances involved become substantial, orbital relays.

d. Lunar Distances

Extending to lunar distances, the problems heretofore noted generally become more difficult. The information rate, power, and bandwidth tradeoffs become more critical. They are much more closely related to the vehicle itself and to the often limited power and energy available because of booster and spacecraft payload limitations. On the moon, the largely unknown environment makes accurate control more critical. The increase in distance causes severe communication losses due to spreading. At these distances, a new factor, communication time lag, becomes appreciable, and control philosophy must take it into account. Motions of the earth and moon cause the communication path to vary both in direction from an earth receiver and in length, causing doppler effects. Rotation of the earth also restricts the operating window from any single receiving site on earth, such as Goldstone, to about 8–10 hours per earth day.

e. Planetary Distances

Operation on the surface of planets involves all of the above problems, each one being more severe. The most pronounced effects are directly related to the increase in distance of two to three orders of magnitude, compared with lunar operations. Communication lags are measured in minutes rather than seconds, and spreading losses are much greater. While the distances involved in interplanetary control make antenna directivity more important, the more complex motions of planets make it more difficult to achieve, and these motions also make operating windows much more restrictive.

In summary, the difficulty of the control problem tends to expand hierarchically with distance. This difficulty increases in discrete steps through the introduction of new problems at greater distances. As was shown in Table 1-1, problems existing at lesser distances carry over and frequently become more critical and more severe. This tendency, in turn, forces an increasing interdependency of the elements of any remote vehicle control system, such that the parameters of any one element cannot be meaningfully determined without relating that element to all of the other elements in a tightly knit system approach.

Thus, the remote control of vehicle motion at lunar and planetary distances involves a complex interplay of several elements:

- Environment (especially terrain)
- Roving vehicle mission
- Vehicle (locomotion subsystem)
- Sensors, and associated remote data storage and processing
- Telecommunications, including relay links and the DSIF/GCS (Deep Space Instrumentation Facility/Ground Communication System)
- Operational support equipment, including SFOF (Space Flight Operations Facility) data processing, storage, and display equipment
- Operator(s), procedures, and software.

In synthesizing control systems to perform given missions all of these elements must be carefully taken into account, and they must be optimized as an integrated system.

### 1.4.2 Elements of the Motion Control Problem

Control itself consists of three basic actions – observation, decision, and command, as shown in Figure 1-1. Observation involves sensing the immediate surroundings of the vehicle by visual or other techniques, and consists of the detection, identification, measurement and reporting of mobility hazards out to a range at least as great as the travel distance of the vehicle between the next command and the next observation.

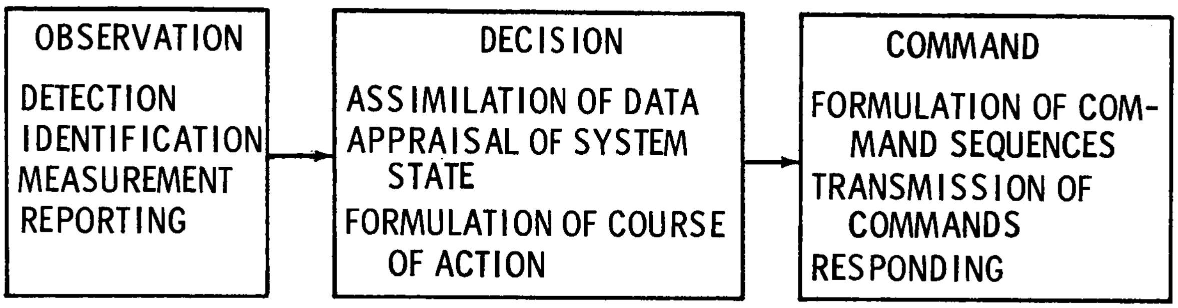


Figure 1-1 Elements of Vehicle Control

The decision process involves the assimilation of all of the observed data, evaluation of their significance and, in the context of some desired locomotion objective, the formulation of a course of action designed to move the roving vehicle safely and efficiently toward the objective. The decision process may be supported by such information storage, display, and simulation capabilities as are necessary to provide the operator with available information of his choosing, and which may enable him to pretest the effects of commands prior to their actual transmission.

The final action in the control process consists of the formulation and transmission of a specific start, stop, or steer command, or a sequence of such commands, or a destination command, which will cause the vehicle to move along the desired course. Implied in this action is the capability of the system to respond appropriately.

Of the three elements above, observation and decision-making are the most complex and the most critical. The successful attainment of mission objectives is crucially dependent upon accurate perception and avoidance of hazardous situations. The efficiency and efficacy of the decision and command functions are contingent upon both the quantity and the quality of sensor data available. In turn, the requirements for sensory data and the number of commands can be reduced by proper information storage, processing, and retrieval in the ground support complex.

Herein lies the crux of the control problem – how to obtain and assimilate sensor data in sufficient quantity and quality to maximize the payoff in terms of specific mission objectives. This involves tradeoffs among all elements of the system and also involves both the mission itself and the nature of the terrain.

## 1.5 GROUNDRULES OF THE STUDY

During the course of the study certain groundrules were established. These tended to bound the study and to channel the effort into the areas of most immediate interest to JPL. These groundrules were as follows:

- Consider that the mission is basically to move out of the contaminated landing area, the minimum radius of interest being 2000 feet. Vehicles should not be range-limited, however, and ranges of hundreds of miles may be of interest on later missions.
- Energy reserve is needed on vehicles to do useful work in addition to locomotion requirements.
- Planetary considerations should be limited to Mars for the present.
- No immediate attention should be given to missions on the far side of the moon nor in the higher latitudes of Mars.
- Vehicle gross weights in the range of 750–900 pounds are of primary interest for both lunar and planetary cases.

# 2.0 RVMC SYSTEM CONSTRAINTS

In most system problems one is faced with certain constraints within which the design of the system is confined. In the case of extra-terrestrial roving vehicle motion control, the most obvious and inviolate of these are imposed by astrodynamic and astrophysical situations - communication distances, relative movements of the earth, moon, and planets, in situ levels of illumination, surface properties, radiation levels, etc.

It is further assumed, for purposes of the study, that certain other practical constraints exist. These are assumed for the purpose of realistically bounding system cost and weight within the general time frame of interest. In particular it is assumed that system masses and form factors must be consistent with existing or planned launch vehicles. Further, it is assumed that major changes in the Deep Space Network are limited to those currently planned and described in References 5 and 6.

## 2.1 VEHICLE GROSS WEIGHT

Only a few sources were uncovered in this study that give realistic landed payload data for Mars, broken down in such a manner as to facilitate extracting roving vehicle weights. The most useful reference(7) covers Voyager Mars opportunities from 1973 to 1984 using a Saturn V launch vehicle with certain assumed contingency factors. The weight breakdowns shown in Table 2-1 are from that study and postulate a growth with time. They are based on an assumption of two identical flight capsules per Saturn V launch vehicle.

Table 2-1
FLIGHT CAPSULE BREAKDOWNS

| | Early First Generation (lb) | Intermediate (lb) | Late Advanced (lb) |
|---|---|---|---|
| Landed Science | 400 | 660 | 1070 |
| Landed Science Support | 1070 | 1070 | 1070 |
| Subtotal | 1470 | 1730 | 2140 |
| Entry Payload | 45 | 45 | 45 |
| Capsule Bus Inert Weight | 2265 | 2240 | 2260 |
| Heat Shield | 1050 | 1050 | 1050 |
| Terminal Propellant | 820 | 900 | 1090 |
| De-Orbit Propellant | 550 | 580 | 640 |
| Cannister | 785 | 785 | 785 |
| Total | 6985 | 7330 | 8010 |

All or part of the landed science and landed science support allotment could be assigned to the gross weight of a roving vehicle. If the roving vehicle were to constitute all of the landed payload it seems reasonable also that a small portion of the inert weight of the bus could also be assigned to the structure of the roving vehicle by using judicious design integration methods, and on the later missions it is quite likely that the entry payload weight could be absorbed into the roving vehicle. Therefore astrodynamic constraints with the Saturn V launch vehicle place an upper bound of about 2500 pounds on the gross weight of the Martian roving vehicle. If one capsule were launched on a Saturn V this could conceivably exceed 4000 pounds.

A rough measure of the maximum weight of roving vehicles for the moon is provided by the MOLAB,[8] designed for a Saturn V/modified LM delivery system. The MOLAB design goal was 6000 lb and it constituted essentially all of the payload.

Vehicles having gross weights under 100 or 150 lb have very limited use. Although vehicles as small as 40 lb have been designed for lunar exploration, the study assumes a lower limit of 100 lb for both lunar and Martian vehicles.

Recent analyses of hypothetical Martian and lunar surface missions have indicated a desirability for vehicles having gross weights in the range of 750–900 lb. Therefore, emphasis in the analysis was placed on vehicles in this approximate weight class whenever weight was a factor.

## 2.2 COMMUNICATION DISTANCE

Communication distance between the earth and Mars varies from about $55 \times 10^6$ km to $400 \times 10^6$ km. Typically, for a 1973 Type I trajectory, the distance at arrival would be about $180 \times 10^6$ km and would increase to nearly $400 \times 10^6$ km, 8-1/2 months later. Thus, for any extended mission the system must be able to accommodate a fairly wide range of interplanetary distances. For any given system this would almost certainly involve some performance variability with time.

Figure 2-1, adapted from Reference 7, shows the communication distance in AU between the earth and Mars over the entire 1973–1985 period. (1 AU = $149.599 \times 10^6$ km).

The communication distance gives rise to two operational factors of major importance. The first is a time lag because of the finite propagation velocity and the second is

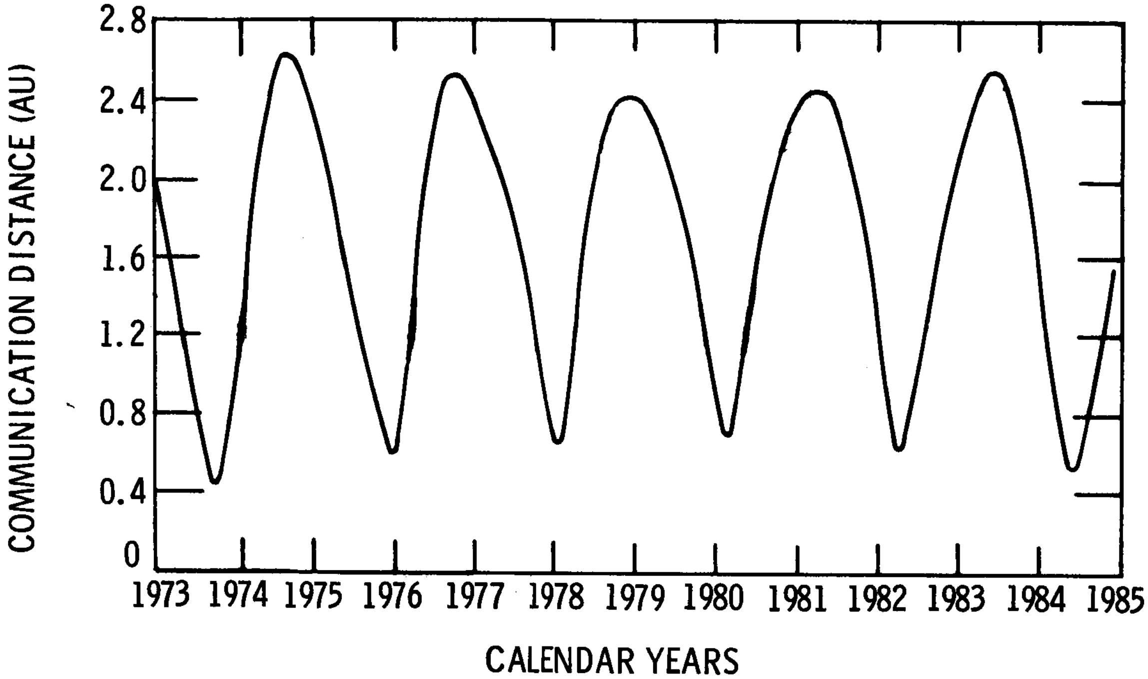


Figure 2-1 Earth-Mars Communication Range

propagation spreading loss according to an inverse square law. In the case of Mars the one-way communication delay ranges from about three to twenty-two minutes. The spreading loss (or free-space loss) is $(4\pi R/\lambda)^2$ and varies from about 254 to 272 dB at S-band.

The earth-moon communication distance is relatively constant, the lunar orbit having a mean eccentricity of only 0.05. The mean distance is $384.4 \times 10^3$ km, giving rise to a one-way time delay of 1.28 seconds and a spreading loss of 211 dB.

## 2.3 OPERATING WINDOWS

In the case of Mars, the periods during which communication with earth is possible can become quite restricted because of the rotation of the planet. Where operation depends upon continuous or intermittent communication between the earth and Mars, this can seriously hamper operations by reducing operating time to a maximum of less than about twelve hours per day. This may be still further reduced by the effect of the difference in Martian latitude between the roving vehicle location and the sub-earth point. If the landing site latitude and the declination of the earth are separated by more than

90 degrees, the earth ceases to be visible at all. Finally, because of multipath and masking effects it can be assumed that the earth is effectively visible for communication purposes only after it has risen to a given minimum elevation angle.

Figure 2-2, adapted from Reference 7, shows these effects under the assumption that the minimum elevation of the earth for effective communication is 30 degrees.

In addition to the restrictions on operating window which arise from the latitude difference between roving vehicle and earth, it may be required with certain system configurations that the sun be visible at the time of transmission to earth. This might arise from illumination requirements for picture taking, or from power requirements, for example, where solar panels are used. The angle at Mars between the lines of sight to the sun and the earth is termed the cone angle. As seen in Figure 2-3, the sun and earth are both visible over the angle $\alpha$, which is $180^{\circ}$ less the cone angle, measured in the Sun-Mars-Earth plane. Since the sun and earth are not necessarily in the Martian equatorial plane nor is the roving vehicle, the geometry is more complicated than shown in Figure 2-3. Figure 2-4, adapted from Reference 9, shows the variation of cone angle with time for a typical Martian opportunity (1975).

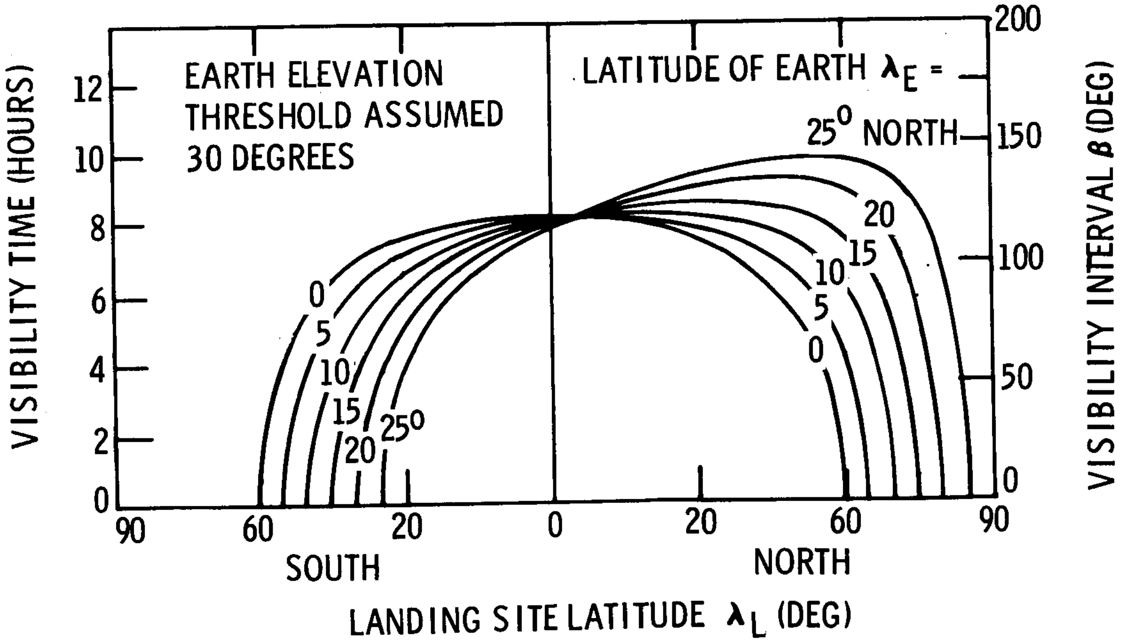


Figure 2-2 Earth Visibility of Lander

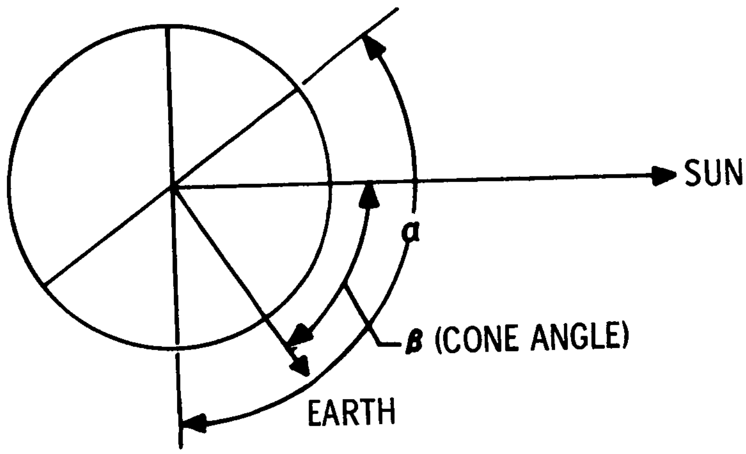


Figure 2-3 Cone Angle

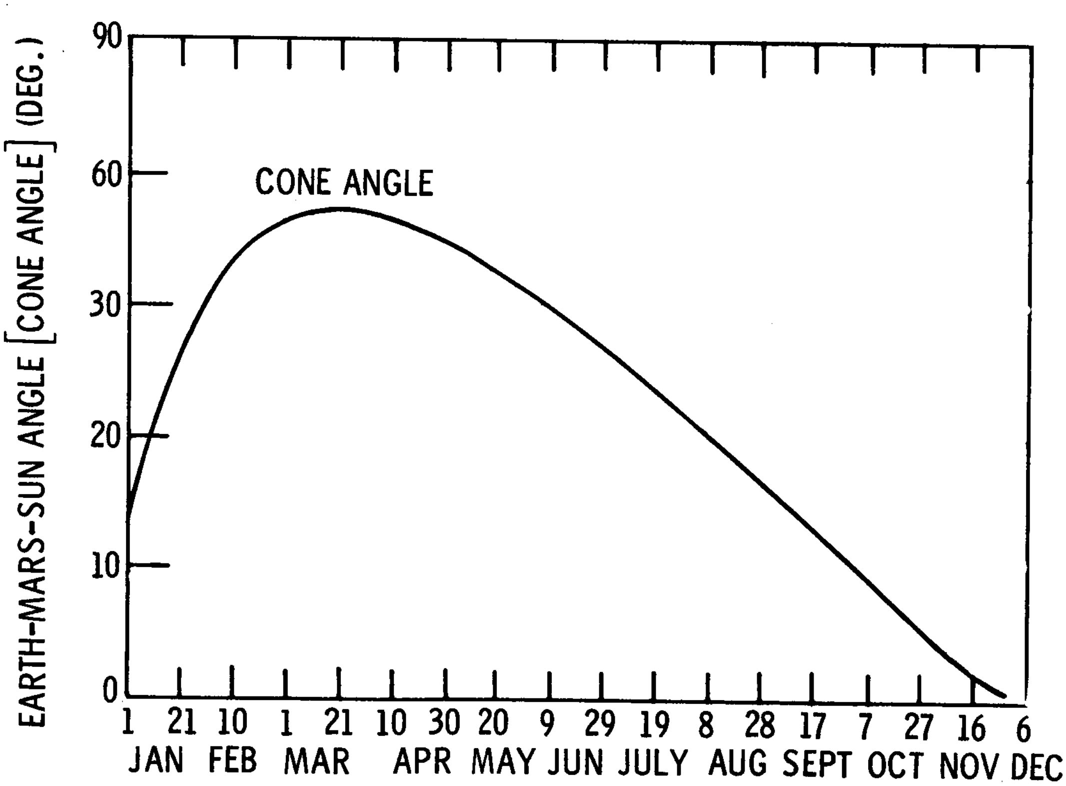


Figure 2-4 Earth-Mars-Sun Angle (Cone Angle) vs Time 1975

For lunar operations most of the above restrictions on operations do not apply, since the moon is in a geocentric orbit with the same face always toward the earth. Any such restrictions that do apply would arise from the different rotational rates of the earth and moon. However, as is discussed in Section 2.5 below, the DSN (Deep Space Network) provides uninterrupted communication capability through the use of stations located on the earth at approximately 120-degree separation in longitude.

It is true that there will be periods when the sun and earth are not simultaneously visible from operating sites on the near face of the moon. Since the earth is always visible, these periods will be exactly half the lunar synodic day, or 14.8 earth-days.

## 2.4 ASTROPHYSICAL CONSTRAINTS

There are many astrophysical constraints under which roving vehicles (and their motion control systems) must operate. These include temperatures, surface properties (both chemical and physical), hard and soft radiation and atmospheric constituents and properties. Most of these, while very important at the hardware design stage, are not of major significance to the problem of motion control insofar as it is considered in this study.

Two of these constraints are worth noting however. The level of soft radiation in the visible spectrum has a direct effect on the choice and effectiveness of certain types of sensors. In the case of Mars, there appear to be color variations from reddish tints or bright pink to nearly crimson in some regions. Reference 10 estimates the range of albedo for the light areas in the visible spectrum at 0.15 to 0.20. When solar energy is to be converted to electrical energy the solar constant is also important. Because of the eccentricity of the Martian orbit the solar constant varies from about 0.050 to 0.074 watts/cm$^2$.

Results of a photometric study by RCA[11] show that luminance distributions on the moon will not generally resemble visual experience on earth. This is due to the high backscatter of the lunar photometric function. The glare pattern below the sun apparently will not exist on the moon due to the lack of specular reflection.

The other astrophysical characteristic of importance to RVMC is the Martian atmosphere, which has an indirect effect. Because of biological quarantine restrictions on Mars, the atmosphere of the planet requires that orbiter spacecraft altitudes be quite great. This, in turn makes it unlikely that there will be useful orbiter pictures of Mars at resolutions comparable to the dimensions of vehicles. Thus, detailed path planning using such pictures is effectively eliminated as a possible approach on Mars.

## 2.5 DEEP SPACE NETWORK

It is assumed for this study that all intelligence regarding the performance and status of a lunar or Martian vehicle must be obtained through the JPL/NASA Deep Space Network. Plans for improving the capabilities of the DSN have been described in Reference 6 covering the period through the mid-1970's. This description, salient points of which are discussed below, is assumed to be a basic RVMC constraint. Where it becomes apparent that substantial improvements in RVMC performance could be realized through changes in the DSN, these are noted. No judgment is rendered as to the advisability of such changes, since it depends on many important factors outside the scope of this study, e.g., technical feasibility, costs, logistics, and overall policy.

a. Deep Space Instrumentation Facility (DSIF). By the early 1970's the DSIF will consist of one network of three 210-foot antennas and a second network of 85-foot antennas, located at approximately 120$^{o}$ intervals in longitude.

Table 2-2 lists the projected characteristics of the DSIF stations that influence the bit rates for the Martian and lunar channels. Four selectable predetection bandwidths (1 dB) will be available at 10 MHz as follows: 4.5 kHz max., 20.2 kHz max., 420 kHz max., and 2.2 MHz max. The DSIF stations utilize PCM/PSK/PM modulation systems.

Table 2-2
DSIF CHARACTERISTICS

| | 85-foot Antenna | 210-foot Antenna |
|---|---|---|
| Transmitter Power | 100 kw Max. | 400 kw Max. |
| Antenna Gain, Nominal | | |
| Transmit (2110-2121 MHz) | 51 dB | 60 dB |
| Receive (2290-2300 MHz) | 53 dB | 61 dB |
| Antenna Beamwidth (Half-Power) | | |
| Transmit | 0.36 deg | 0.145 deg |
| Receive | 0.33 deg | 0.135 deg |
| Receiving System Noise Temp (Maser) | 55$^{o}$K | 45$^{o}$K |

A command system data-processing and transmitter phase-modulation capability is provided at each Deep Space Station. A command verification-transmission technique is utilized whereby the incoming command message is verified and translated into the proper spacecraft language, and then is transmitted. During transmission, a bit-by-bit comparison is made for final verification. At present SDS-920 computers are used for telemetry and command data processing, but these machines are to be modified to accommodate Martian requirements. Some limited analog-digital capability for handling analog signals is planned, but significant analog processing (such as analog TV, for example) is not foreseen.

b. Ground Communication System (GCS). The Ground Communications System consists of voice, teletype, and high-speed data circuits between each overseas station, the Cape Kennedy Station, and the SFOF. The functions of the GCS are: (1) to relay data and information obtained by the DSIF to the Space Flight Operations Facility, and (2) to relay status information, operational instructions, and spacecraft commands from the SFOF to the DSIF. By 1973 it is expected that all GCS overseas communications will be satellite-derived. The communication capability of a typical overseas DSIF station with SFOF is planned to be as follows:

1. Teletype: 4–6 circuits, error rate $10^{-5}$
2. High speed: 1–2 circuits, 2400 to 4800 b/s, error rate $10^{-5}$
3. Voice: 2 circuits
4. Wideband: 4.5 MHz video one-way from DSS to SFOF (limited time-shared usage)
5. Wideband digital channel: 8–10 kbps (if requirement is identified at least three years prior to use).

c. Space Flight Operations Facility (SFOF). The Space Flight Operations Facility is a data processing entity which will allow, for two or more missions simultaneously, the efficient coordination and direction of mission activities; command, monitor, and control of spacecraft performance; acquisition, analysis, and evaluation of mission experimental data; two-way communications between earth and spacecraft; and finally, tracking and position data processing over planetary distances.

Handling the enormous quantities of data derived from the tracking, telemetry, and operation of a spacecraft requires a central control agency which can process and display received information reliably and quickly, can exert coordinated command functions via worldwide communications network and spacecraft facilities, and can provide for efficient implementation of the personnel effort required for space missions.

Different missions impose different requirements upon the data processing complex. The SFOF must be specifically configured to handle each mission. However, the basic hardware functions remain essentially the same. It is expected that the change in configuration will be accomplished almost entirely by software modifications which can be carried out quickly and at a fraction of the cost involved in hardware changes.

In the case of a roving vehicle mission, work stations would, insofar as possible, be configured from existing hardware for locomotion control, sensor control, telecommunications control, and monitor/command functions as required by mission objectives.

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# 3.0 MISSIONS AND TERRAIN

As noted in Section 1, the system design of the RVMC depends in part on the mission of the roving vehicle and the operating environment, especially the terrain. At the outset of the study it was envisioned that a set of missions would be postulated. It soon became apparent that, in a study of this type, such an approach would run the risk of prematurely and perhaps inadvertently restricting the scope of the study.

For this reason, it was decided that it would be preferable to characterize missions in terms of a set of functional or operational elements which tend specifically to define the control problem. In the case of terrain, it was decided that, rather than attempting to derive a model of the lunar or Martian surface, it would be preferable to postulate a spectrum of arbitrary terrain models, each of which presented a somewhat different problem from the motion control standpoint. The following is a brief discussion of the mission and terrain characterization which resulted. It will be seen that the outcome is more properly described as a set of operational modes, any or all of which might be used on a given mission, depending upon circumstances.

## 3.1 SUMMARY OF MISSION ELEMENTS

Two basic functions of the control system can be identified at the outset.

- Vehicle Functions

  F1) To effect safe transfer of the roving vehicle to a specified point.

  F2) To orient the vehicle in a prescribed manner with respect to another (stationary) object and perhaps to effect some sort of physical connection with it.

The means of accomplishing F1 are directly influenced by the manner in which the specified point is chosen and by the parameters used to define the point. The destination may be chosen by one of three methods.

- Manner of Choosing Destination

  M1) Destination points are pre-programmed based on *a priori* knowledge, e.g., orbiter pictures, and/or experiment requirements.

M2) The earth-based mission control station makes all decisions regarding destinations based on mission requirements and prior data returned from the mission.

M3) The control system chooses the destination based on programmed decision processes and vehicle-borne sensors.

These methods refer to the choice of major destinations and/or to a sequence of minor intermediate destinations, rather than to the detailed control decisions. In other words, included here is the function of general path planning. M1 might be used when detailed a priori knowledge of points of interest exists or when the location of experimental packages in a specific geometrical array is desired. M2 is appropriate when a priori knowledge of points of interest is scanty, when missions are of a sampling type, or when system constraints prohibit the degree of automaticity required of M1 or M3. M3, the most sophisticated, is attractive when the conditions appropriate to M2 exist, but when operating windows or data rates seriously degrade mission efficiency under M2. Here the control system must locate and evaluate points of interest, and automatically devise a plan to reach these points.

The destination may be specified in a number of ways resulting in different control requirements.

- Manner of Specifying Destination

C1) Destination is specified in terms of planar coordinates, either planetocentric or referred to an arbitrary reference point such as the landing site.

C2) The range is specified, but the bearing is not critical.

C3) The bearing is specified, but the range is not critical.

C4) The destination is specified in terms of some experimental requirement other than range or bearing (e.g., gain a high point).

C5) The destination is a point previously occupied by the roving vehicle.

Concomitant with the ability to reach the destination, however specified, is the ability to navigate, i.e., to determine the roving vehicle's current location. For some missions the navigation requirements will be determined by the manner of specifying the destination. For others, the a posteriori ability to locate experimental points accurately is more important than the ability to reach a specific point. This leads to two general navigational situations.

• Navigation Requirements

N1) Navigation requirements are no more stringent than the requirements implied by the description of the destination.

N2) Navigation requirements are significantly more stringent than those implied by the destination description.

In the generation and execution of a path plan to reach a given destination efficiently, routine decisions regarding starts, stops, steering, etc., may be carried out in either of two basic ways.

• Method of Making Routine Control Decisions

D1) Decisions are routinely made by the earth-based operations control station.

D2) Decisions are routinely made on the vehicle in accordance with pre-programmed (possibly adaptive) instruction.

Three terrain models were postulated. These models are described qualitatively, although for operational simulation it would be desirable to develop quantitative, perhaps stochastic, models which could be described analytically or simulated on a computer.

• Terrains

T1) This terrain consists of a gently rolling terrain having no sharply defined features. Occasional slopes exceeding the capability of the vehicle may be encountered and must be guarded against, but, for the most part, vehicle control will consist of confirming the safety of a chosen course of action and of choosing paths for maximizing mission efficiency from the standpoint of either velocity or energy consumption. Typical of this model is the terrain at the impact point of Ranger 7.

T2) This terrain consists of Model 1 overlaid with sharp features (rocks, cliffs, crevices, holes, etc.), most of which are within the capability of the vehicle to negotiate. The model contains a sufficient number of hazards to mobility that care must be routinely exercised, but a safe path is readily found. Most control decisions will consist of verifying safe passage and choosing between obstacle negotiation and obstacle avoidance, with the latter being the usual choice.

T3) This terrain is a more severe version of Model 2, where the frequency of hazardous features is so great as to constitute a continuous threat to vehicle safety, and a safe path may even be nonexistent. Here, control activity must be routinely concerned with evaluating the degree of threat to vehicle safety with the ever-present possibility that an erroneous decision will be not merely inefficient, but may terminate the mission.

To complete the characterization of the control problem one needs an additional dimension, viz., the body being explored.

- Survey Body

  B1) Moon
  B2) Mars
  B3) Other.

## 3.2 ANALYSIS OF MISSION ELEMENTS

If all possible combinations of these characteristics were to be considered independently possible, it is seen that there are 1080 separate cases. Individual consideration of each case would have constituted an unmanageably large problem for the present RVMC study. Even a cursory examination, however, shows that not all cases need be considered, since some combinations are illogical and others are uninteresting. The characteristics were therefore analyzed as discussed below to identify combinations of interest and to reduce the list to a manageable subset while retaining the maximum amount of generality possible.

It is unlikely that any system would be of interest if it did not incorporate the capability to transfer the roving vehicle to a specified point (Function F1 above). Therefore, one can assume that whenever a system is required to have the capability to orient the roving vehicle in a prescribed manner (F2), it will also have F1 capability. The reverse, unfortunately, is not necessarily true. Translational capability need not always be accompanied by the specialized orientation capability implied in F2.

In many cases, the requirement to orient the roving vehicle in a prescribed manner would entail capabilities not unlike those needed for translation over extremely rough terrain (F1 over terrain T3). In other cases, though, F2 might entail very specialized maneuvers and operations uniquely associated with the particular task at hand. The number of such possibilities seems virtually limitless. It would not seem to be very fruitful to pursue each of these possibilities in this study. Rather, each case should be considered when it arises as a requirement of a specific mission, and appropriate hardware and software added as needed. Thus, for this study Function F2 was not covered as a separate case. Function F1 was considered the basic function of the RVMC system, i.e., safe transfer of a payload to a specified point.

Of the three modes of choosing the destination, preprogramming (or M1) is appropriate when considerable detailed data are available prior to launch or when experimental requirements such as a specific geometrical array of destinations is imposed. It might also apply in some cases where previous traverses are to be repeated. In none of these cases does it appear that mode M1 would lead to system configurations which are sufficiently different from both M2 and M3 to warrant consideration of M1 as a separate case. It is true that, in some cases, the considerations which might make M1 appropriate, might also have a significant effect on operational strategy and even on hardware. For example, when repeated traverses are made over the same terrain, information gathered on early traverses might be used to great advantage on subsequent traverses, given the capability to store, analyze, and apply this information. Such possibilities can and should also be included under systems using methods M2 or M3. It appears then that method M1, if unique at all, is unique only in requiring the capability to store and retrieve the data needed to characterize the destination, and so need not be considered further. Therefore, M1 was dropped from further consideration. Systems having M2 and M3 capability were considered.

Each of the five means of specifying the destination, C1 through C5, may entail distinct configurational features. To the extent that each is independently important, it should perhaps be considered. It was felt however, that systems capable only of achieving a given range (C2) or a given bearing (C3) are not of particular interest even if the corresponding system configurations might somehow be unique. For example, early missions might require the roving vehicle simply to move a given distance from the landing site to acquire an uncontaminated sample and return. There would be a clear desirability however, even on early missions, to have growth potential to handle bearing as well, thereby constraining the range capability to be compatible with the later combined range/bearing (C1) characterization. One can also argue that the kind of capabilities implied in C2 and C3 are available in any system capable of C1 (although it is also true that their combined presence might have some effect upon the manner in which the capabilities are achieved). These considerations led to the elimination of C2 and C3 from further consideration except as degraded modes of operation under C1.

The specification of the destination in terms of experiment requirements (C4), as with F2, is virtually limitless in its possibilities. Many of these possibilities are subsumed under C1, but others are quite specialized, e.g., seek a high point or a low point, a hot spot or a cold spot, a hard region or a soft region. These specialized cases are not of major interest independently, but only in combination with broader capabilities. Each must be considered individually in the light of its own requirements and appropriate capabilities must be added. Since it is not basic to the roving vehicle control problem, C4 was eliminated from further consideration.

Return to a point previously occupied (C5) may be embodied in C1, but may sometimes require significantly better guidance and navigational capability. It may also make use of techniques and strategies generally not applicable to initial traverses to points. For example, in the case of return to the lander, terminal aids on the lander itself might be considered. In other cases it might require or benefit from the assimilation and use of data gathered on earlier traverses. Because of these unique features of C5 it could not be dismissed from consideration. It is probably desirable however that any system capable of transfer to a point previously occupied also have the capability to transfer to a point not previously occupied. Then C5 occurs only in combination with C1 and it seems appropriate to consider C1 as "standard" and C5 as an "optional extra." Systems may then be considered from the standpoint of providing C1 capability and then the implications of adding C5 capability may be considered separately.

The breakdown of navigation requirements is couched in terms of the required accuracy relative to that embodied in the description of the destination. Underlying this division was the supposition that one might frequently be content to arrive anywhere in a given area surrounding a point or at any feature having specified properties, but, once having arrived there, might want a rather precise value to locate the point. The real division here is thus not on the basis of navigational accuracy, per se, but on the basis of a priori and a posteriori requirements. Stated in another almost equivalent manner, this is the classical division between guidance and navigation. The former involves path planning and issuance of commands commensurate with the achievement of a specified goal, and the latter involves the determination of present position at some chosen point(s) on the traverse. The two navigational options N1 and N2 are thus seen as not mutually exclusive, but complementary functions, both of which will generally be present, even if in very rudimentary form. Therefore, rather than eliminating either one, they were combined into a single requirement, N1, 2.

The process of making routine control decisions and formulating detailed commands may be done either on earth or on the roving vehicle, as symbolized by D1 and D2. However, the considerations leading to a system having the sophistication to plan its own path or to make its own choice of destination (M3) would hardly be consistent with earth-based routine detailed control (D1), except as an override or emergency mode. Since it must always be assumed that earth-based control can override at any time, this is included in D2.

The use of on-board routine control capability (D2) in conjunction with earth-based choice of the destination objectives is not inconsistent and must be retained as a rational and interesting possibility. Therefore, of the four possible combinations of M2 and M3 with D1 and D2 (M1 having been eliminated above), only three are worth further consideration.

It may reasonably be postulated that no system of interest would be limited to a single kind of terrain, even though the three terrains T1 through T3 constitute basically different problems from the control standpoint. The decision was made somewhat arbitrarily to impose the condition that all systems must have the dual capability of operating over either T1 or T2, and must be configured to be consistent with either or both. One might further include T3 in this combination, but it seems that this would impose sufficiently different requirements (which under some conditions may not even be feasible to meet) that it should be considered separately. One can reasonably suppose, however, that any system having T3 capability must also have T1 and T2 capability. Therefore, T3 capability was treated as an "optional extra" and T1/T2 capability as "standard."

Finally ground rules of the study listed in Section 1.5 eliminate bodies to be explored other than the moon and Mars from consideration. Therefore only B1 and B2 need be considered in any mission characterizations for the present study.

## 3.3 BASIC RVMC MISSIONS

On the basis of these considerations, a family tree of functional elements may be derived as in Figure 3-1. The number of basic missions is reduced to six. The resulting six mission characterizations, A through F, are briefly described below. All are considered to be traverses to a prespecified destination over terrain which has some regions which are gentle rolling plains with occasional treacherous slopes and/or soft soil and

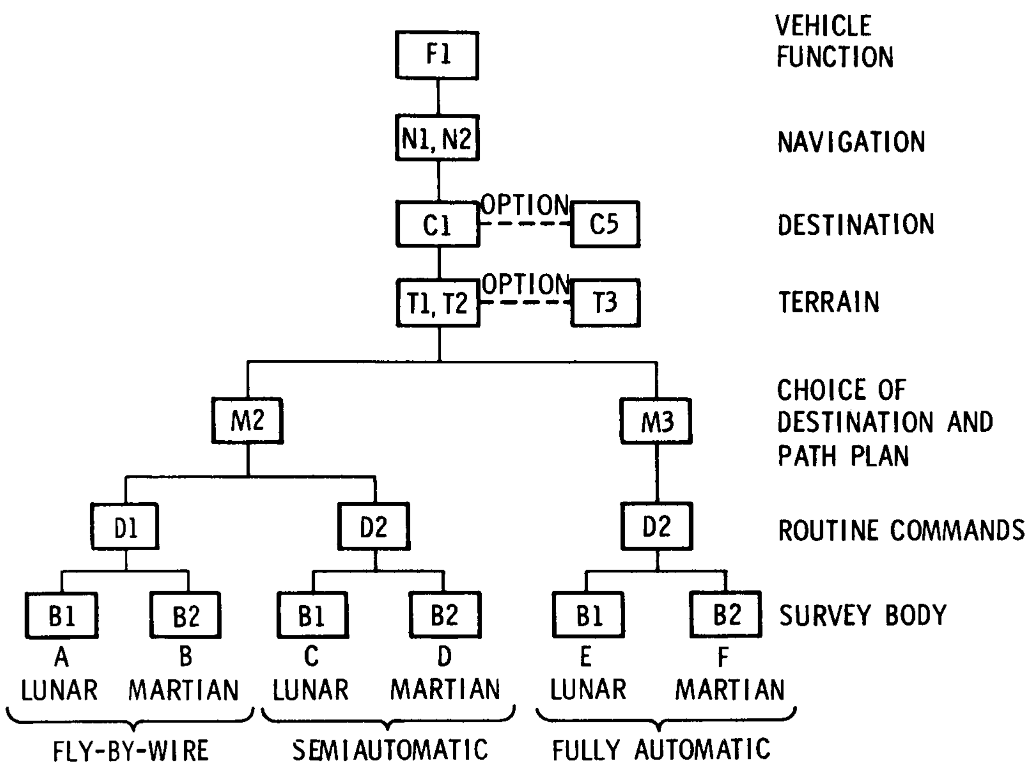



Figure 3-1 Mission Family Tree

other regions which are moderately rough and strewn with angular debris of varying sizes up to and sometimes exceeding the safe capability of the vehicle to negotiate, but where a safe path is readily available at all times. All involve the capability to provide guidance and navigation accuracy commensurate with mission scientific objectives.

A. On the moon, traverse to a given point, the location of which is specified by mission control in planar coordinates with a given permissible error. Provide mobility and steering as required to realize the specified accuracy and, from time to time, on command from earth, report present position in suitable coordinates to some specified accuracy. Respond to routine commands originating on earth for both detailed mobility functions and control sensor functions.

B. Same as A, except on Mars.

C. On the moon, traverse to a given point, the location of which is specified by mission control in planar coordinates with a given permissible error. Provide mobility and steering as required to realize the specified accuracy, and from time to time, according to preprogrammed instructions, report present position in suitable coordinates to some specified accuracy. Automatically generate and respond to all routine commands for both detailed mobility functions and control sensor functions. Provide capability for earth override of any on-board program or decision process and for reprogramming on-board logic as desired.

D. Same as C, except on Mars.

E. On the moon, traverse to a given point, the location of which may be determined by on-board decision processes and specified in planar coordinates with a given permissible error. Provide automatic path planning and steering functions suitable to realize the specified accuracy, and from time to time, according to preprogrammed instructions, record present position in suitable coordinates to some specified accuracy. Automatically generate and respond to all routine commands for both detailed mobility functions and control sensor functions. Provide capability to store navigational and control sensor data and report out these data either on command or according to preprogrammed instructions. Provide capability for earth override of any on-board program or decision process and for reprogramming on-board logic as desired. Provide capability for complete earth control at possibly degraded performance levels.

F. Same as E, except on Mars.

The resulting mission characterizations tend to describe modes of operation as well as missions. There are three levels of control sophistication represented, corresponding to increasing degrees of roving vehicle autonomy. For purposes of identifying these three modes the following terminology was adopted.

<u>Fly-by-wire.</u> This is the least sophisticated of the three. It requires essentially all control decisions to be made on earth.

<u>Semi-automatic.</u> In this mode, routine start, stop, and steering commands are generated on-board the roving vehicle in accordance with a destination and general path plan formulated on earth.

<u>Fully automatic.</u> Here the destination and/or path plan are chosen by preprogrammed on-board decision processes. Earth control functions are limited to monitoring and override, and possible reprogramming on the basis of early experience on the mission. This mode also includes possible adaptive and learning capabilities which might be incorporated on the roving vehicle.

Probably no practical system will answer exactly to these descriptions. There will always be some degree of overlap. For example, in the fly-by-wire mode, one would probably always include means for abruptly stopping the roving vehicle whenever it encounters hazards which threaten to permanently incapacitate it. Since transmission and decision times would generally not allow this action to originate on earth, a degree of on-board decision capability must be incorporated. Similarly, it seems likely that either of the more sophisticated modes should incorporate the capability to operate in the more basic modes as a backup, override, or failure capability.

Nevertheless the above characterizations have proven useful in distinguishing between fundamentally different modes of operation and are used in the following discussion with the understanding that they allow a reasonable amount of flexibility commensurate with practical considerations. In the following sections, the implications of these missions or modes are examined from the standpoint of system requirements, and general system configurations are defined for each.

# 4.0 SYSTEMS FUNCTIONAL REQUIREMENTS ANALYSES

A requirements analysis proceeds by stating system requirements at a general level and expanding them to successively more definitive levels. This is done by breaking down each requirement in greater detail. If the methods for going from one level to the next are chosen carefully, eventually a level is attained at which useful system configurations can be constructed.

When these configurations are not intended to deal with actual hardware, personnel requirements, or specific methodologies, the ultimate means of meeting a requirement need not be prescribed.

In this study the requirements breakdown proceeds as follows.

## 4.1 TOP-LEVEL RVMC FUNCTIONAL REQUIREMENTS

Top-level control requirements for an RVMC system can be expressed as functional relationships between a roving vehicle and its control agencies. Simply stated, a requirement exists for a roving vehicle control system which will allow the vehicle to be operated safely on extra-terrestrial surfaces by external and/or internal control in such a manner that scientific instrumentation can be moved from one place to another. Figure 4-1 shows this relationship.

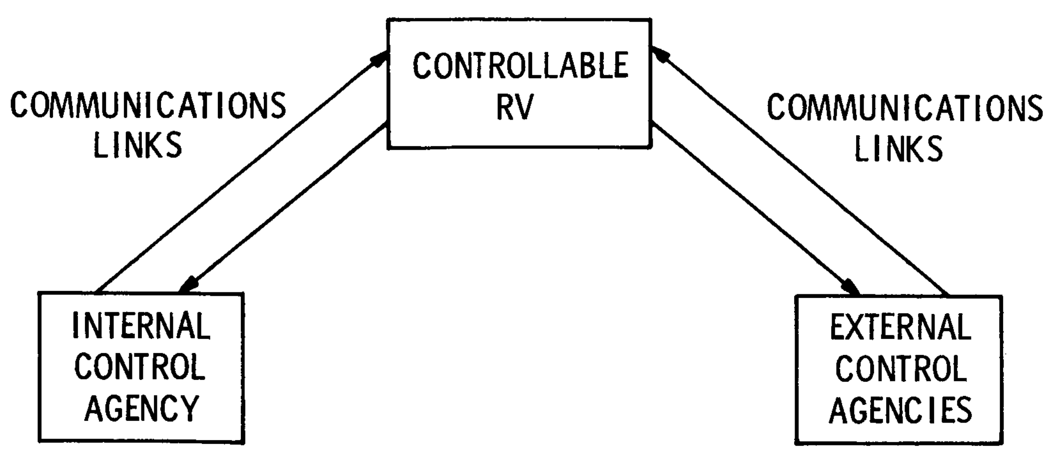



Figure 4-1 Top-Level Configuration of a Controllable RV System

Control may be conceived essentially as consisting of information processing. The overall control function is described here in terms of a set of relationships between paired information-processing functions. In this manner, a first-level breakdown is derived.

## 4.2 FIRST-LEVEL RVMC SYSTEM FUNCTIONAL REQUIREMENTS

A requirement exists for an RVMC system which incorporates the ability to process information relating to the vehicle and/or its control agencies in a manner which will allow

- The sensing and reporting of system states
- The appraising of situations and the making of decisions
- The issuing of system-relevant commands and the responding thereto
- The storing and retrieving of information.

The first-level functional relationships are shown in Figure 4-2.

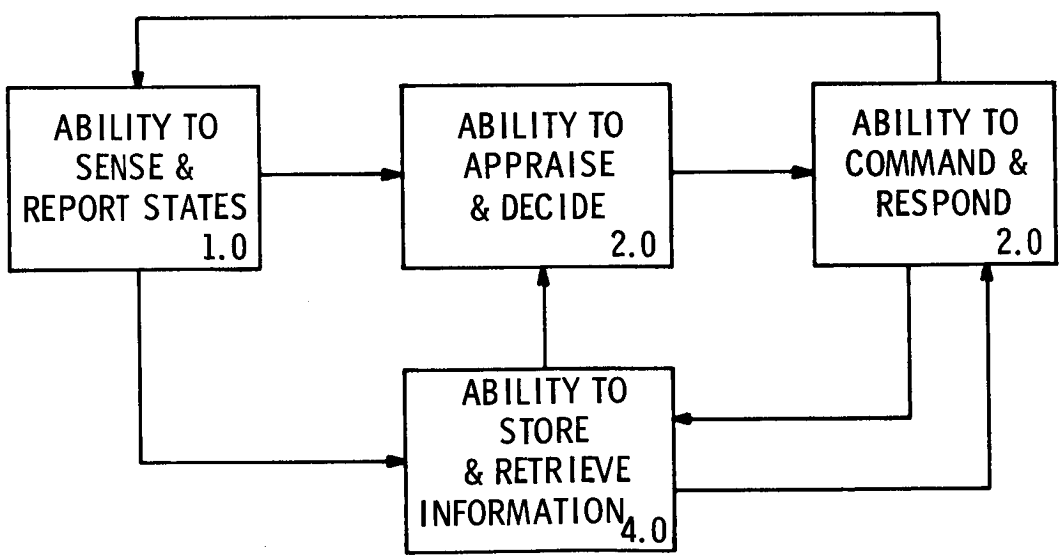



Figure 4-2 Functional Relationships for First-Level Breakdown of RVMC Systems Requirements Based Upon Information Processing Functions

Once information-processing is chosen as the means for structuring the requirements hierarchy, succeeding levels of breakdown are attainable simply by elaborating upon the above information-processing functions. Thus, second-level requirements can be described by specifying what states must be sensed and reported, what appraisals and decisions must be made, what commands the system must process and act upon, and what kind of information must be stored and retrieved.

## 4.3 SECOND-LEVEL SYSTEM REQUIREMENTS

Table 4-1 lists the second-level breakdown of the requirements description.

Table 4-1
SECOND-LEVEL RVMC SYSTEMS REQUIREMENTS BREAKDOWN

| The Ability to Sense and Report States 1.0 | The Ability to Appraise & Decide 2.0 | The Ability to Command & Respond 3.0 | The Ability to Store & Retrieve Information 4.0 |
|---|---|---|---|
| 1.1 RV States<br>1.2 Terrain States<br>1.3 Navigation Parameters<br>1.4 Environmental States | 2.1 Regarding System States<br>2.2 Regarding System Operation<br>2.3 Regarding Mission Conduct | 3.1 Enable and/or Disable Communications System<br>3.2 Operate Sensors<br>3.3 Operate Mobility System<br>3.4 Initiate, Modify, Retain or Abandon Programming | 4.1 Sensor Data<br>4.2 Command Data<br>4.3 Data-Bank Data |

As the development of the systems requirements hierarchy progresses it becomes desirable to specify the functions of sensing, reporting, etc., in greater detail. For this purpose, third and fourth levels are derived.

## 4.4 ADVANCED LEVELS OF RVMC SYSTEMS REQUIREMENTS

The third and fourth levels are obtained by more specific listing of the data being processed. The outline below carries the requirements analyses to the fourth level.

### THIRD AND FOURTH LEVEL SYSTEMS REQUIREMENTS BREAKDOWN

1. THE ABILITY TO SENSE AND REPORT

   1.1 The system must have the ability to sense and report data allowing the determination of RV states.

      1.1.1 RV Attitude

         1.1.1.1 Orientation with respect to local gravity.

         1.1.1.2 Orientation on azimuth with respect to an acceptable horizontal reference.

         1.1.1.3 Orientation of RV with respect to astronomical reference bodies (earth, sun, stars, etc.).

1.1.2 RV Control Variables

1.1.2.1 Steering angle

1.1.2.2 Orientation with respect to an acceptable fiducial reference

1.1.2.3 RV drive speed

1.1.2.4 Braking, in terms of retarding force applied in either continuous or discrete mode, or in terms of deceleration.

1.1.2.5 Sensor operating parameters, including on/off, adjust, orient, override, change sense/report mode.

1.1.2.6 Other; component status, etc.

1.1.3 Engineering Parameters

1.1.3.1 RV temperatures

1.1.3.2 RV power levels

1.1.3.3 RV vibration

1.1.3.4 Shock; time and enumeration data

1.1.3.5 Other; component status, etc.

1.2 The system must have the ability to sense and report data allowing the determination of terrain states.

1.2.1 Obstacles

1.2.1.1 Step heights; distance and bearing from RV

1.2.1.2 Outcroppings, overhangs, hang-ups, cliffs; distance and bearing from RV

1.2.1.3 Fissures; width, distance and bearing from RV

1.2.1.4 Craters; width and depth, distance and bearing from RV

1.2.2 Slopes

1.2.2.1 Angle of inclination of line of maximum slope

1.2.2.2 Azimuth of line of maximum slope with respect to a suitable reference

1.2.3 Unstable Terrain

1.2.3.1 Insecure rocks, potential avalanche sites (distance and bearing)

1.2.3.2 Vulcanism and similar surface phenomena (distance and bearing)

1.2.3.3 Thin crusts overlaying soft soil

1.2.4 Gaps in Terrain Barriers

1.2.4.1 Gap widths and vertical profiles

1.2.4.2 Gap locations in distance and bearing from RV

1.2.5 Soil Parameters

1.2.5.1 Flotation characteristics

1.2.5.2 Impact strength

1.2.5.3 Traction characteristics

1.2.5.4 Resistance to sliding.

1.3 The system must have the ability to sense and report data allowing the determination of navigation parameters.

1.3.1 RV Heading

1.3.1.1 Heading with reference to some fiducial line.

1.3.1.2 Heading with respect to some astronomical reference.

1.3.2 RV Positions

1.3.2.1 With respect to a lunar or planetary coordinate system

1.3.2.2 Relative to landmarks or previous vehicle position.

1.3.3 RV Distance Travelled and Velocity

1.3.3.1 Distance

1.3.3.2 Velocity.

1.4 The system must have the ability to sense and report data allowing the determination of environmental states.

1.4.1 Wind Parameters

1.4.1.1 Direction

1.4.1.2 Velocity

1.4.1.3 Gusts (average and maximum).

1.4.2 Meteorological Phenomena

1.4.2.1 Blowing dust

1.4.2.2 Visibility

1.4.2.3 Cloud coverage.

1.4.3 Ambient Fields

1.4.3.1 Light intensity and direction

1.4.3.2 Temperature and temperature gradients involving external (RV) temperature

1.4.3.3 Magnetic field intensity and direction

1.4.3.4 Other (meteoritic flux, particulate radiation, etc.).

2. THE ABILITY TO APPRAISE AND DECIDE

2.1 The system must have the ability to make appraisals and decisions regarding system states.

2.1.1 RV States

2.1.2 Terrain States

2.1.3 Navigation Parameter States

2.1.4 Environmental States

2.2 The system must have the ability to make appraisals and decisions regarding system operation.

2.2.1 Communication Parameter Selection

2.2.2 Programming Modes (retain, discard, modify)

2.2.3 Choice of Decision/Appraisal Modes

2.2.4 Selection of Sensor Parameters

2.2.5 Selection of Control Commands

2.3 The system must have the ability to make appraisals and decisions regarding mission conduct.

2.3.1 Choice of Mobility Objectives

2.3.2 Risk vs Potential Data Return

2.3.3 Path Planning

2.3.4 Use of Backup Modes and Redundant Systems

3. THE ABILITY TO COMMAND AND RESPOND

3.1 The system must have the ability to give and respond to commands which enable/disable communications systems.

3.1.1 Antenna Control

3.1.1.1 Select antenna

3.1.1.2 Orient antenna

3.1.2 Electric Power Control

3.1.2.1 Enable/disable electric power

3.1.3 Change Communications Parameters

3.1.3.1 Enter/leave transmit mode

3.1.3.2 Enter/leave receive mode

3.1.3.3 Enter/leave other communication states.

3.1.4 Verify Receipt and/or Execution of Communications Commands

3.2 The system must have the ability to give and respond to commands to operate sensors.

3.2.1 Enable/Disable Sensors

3.2.2 Change Sensor Parameters

3.2.3 Orient Sensors

3.2.4 Route Data Flow from Sensors

3.2.5 Override Sensor Activated Functions

3.2.6 Extrapolate Selected Parameters in Distance or Time

3.2.7 Allocate Between Decision Modes and Between Reporting Modes to Maximize System Functioning

3.2.8 Verify Receipt and/or Execution of Sensor Operative Commands

3.3 The system must have the ability to give and respond to commands involving RV mobility.

3.3.1 Readiness Commands

3.3.1.1 Unlock from lander

3.3.1.2 Enable/disable motive power

3.3.1.3 Enable/disable mobility sensors

3.3.1.4 Other (specific to situation)

3.3.2 RV Drive Commands

3.3.2.1 Start

3.3.2.2 Stop

3.3.2.3 Back

3.3.2.4 Accelerate

3.3.2.5 Decelerate

3.3.2.6 Select progress mode

3.3.2.7 Select continuity mode (step or continuous)

3.3.2.8 Brake

3.3.3 Other Commands

3.3.3.1 Verify receive/execute mobility commands

3.3.3.2 Extricate self

3.4 The system must have the ability to give and respond to commands initiating, selecting, modifying or abandoning programming.

3.4.1 From Signal

3.4.2 From Storage

4. THE ABILITY TO STORE AND RETRIEVE DATA

4.1 The system must have the ability to store and retrieve sensor data.

4.1.1 Discrete Status Data

4.1.2 Continuous Status Data

4.1.3 Limits for Sensor Parameter Values

4.1.4 Navigation Parameter Values

4.1.5 Path Planning Data

4.2 The system must have the ability to store and retrieve command data.

4.2.1 Operational Command Data

4.2.1.1 Mobility commands

4.2.1.2 Sensor commands

4.2.1.3 Telecommunications commands

4.2.1.4 Programming commands

4.2.2 Mission Conduct

4.2.2.1 Path planning data

4.2.2.2 Mission strategies

4.2.2.3 Command logic

4.2.2.4 Computation algorithms

4.2.2.5 Destinations

4.3 The system must have the ability to store and retrieve data-bank data.

4.3.1 Derived From Previous Measurements or Experience

4.3.2 Derived From Analysis

## 4.5 USE OF SYSTEMS REQUIREMENTS TO CHARACTERIZE MISSIONS

The statement of the functional requirements for a Roving Vehicle Motion Control system given in the outline above is not made with reference to any specific mission or class of missions. Few, if any, systems would have all of these requirements imposed. Since the RV control function is accomplished by processing relevant information, the requirements for any mission may be derived by extracting those information-processing needs which apply to that mission when it is described in terms of the functional characteristics represented in Figure 3-1.

The functional characteristics do not simply combine additively, but rather, when combined, they give rise to interactions. The requirements imposed by specifying a particular characteristic element may alter the requirements associated with any or all of the remaining elements.

Let [K] represent the group of four mission functional characteristics of Figure 3-1 common to all of the relevant missions, i.e., [F1, N1 and 2, C1, T1 and 2]. Then the single elements [K], [M2], [M3], [D1], [D2], [B1], [B2] may be considered as zero-order interactions. First-order interactions are represented by terms of the type

[K x M2] , [D2 x B2] etc.

Second-order interactions involve three elements

[K x D1 x B2] , [M2 x D1 x B2] etc.

Third-order interactions contain four elements

[K x M2 x D1 x B1] , --- etc.

It will be noted that there are six third-order interactions, each representing one of the six mission control configurations which have been selected as germane to the study, viz.,

[K x M2 x D1 x B1]: Lunar Fly-by-Wire Mission

[K x M2 x D1 x B2]: Martian Fly-by-Wire Mission

[K x M2 x D2 x B1]: Lunar Semi-automatic Mission

[K x M2 x D2 x B2]: Martian Semi-automatic Mission

[K x M3 x D2 x B1]: Lunar Fully Automatic Mission

[K x M3 x D2 x B2]: Martian Fully Automatic Mission.

Interactions between various combinations of the elements may be used to differentiate mission types. For example, if it is desired to compare a general Martian mission with a lunar mission, each may be considered as a first-order interaction of the form

[K' x B1] and [K' x B2] ,

where K' represents those elements which the two missions have in common, and can be expressed as the sum of the requirements associated with all of the mission functional characteristics except B1 and B2.

It should be noted that the requirements of both M2 and M3, as well as those of both D1 and D2 must be included in K'.

In order to characterize missions uniquely, the commonality (in this case K') should be made as small as possible. A method for reducing the commonality between mission types is presented in Section 4.5.1.

While the Mission-Characteristics Tree given in Figure 3-1 defines six individual missions by assigning an appropriate combination of mission functional characteristics to each mission, it is important to note that any given mission differs from another in a manner more complex than that described by the simple presence or absence of requirements associated with the individual characterizing functions. This is partly because these functions interact as noted above. For example, a fully automatic RVMC system specifying Mars as the target body has different requirement implications with regard to automaticity than one specifying the moon as the target body. Thus, each mission-applicable requirement must be studied in relation to the mission as a whole.

There is an additional reason why the specific mission requirements should be examined further. When these requirements are used as a basis for the construction of system functional configurations, differences between missions related to the loading on corresponding communications channels, choices of primary and secondary modes, degrees of confidence in the reliability of certain kinds of data, and other differences related to information processing may be masked by the fact that every existing functional requirement, regardless of its system importance or usage, must be represented in the configuration. Thus, a given item may appear in two configurations, but be used in a vastly different manner or with different duty cycles, etc.

### 4.5.1 Methodology for Mission Differentiation on the Basis of Systems Requirements Characterization

An effort is made in this section to develop a methodology for systematically examining the requirements at the several levels in order to be able to state mission differences with greater specificity than is possible by a simple listing of mission requirements or by general system configuration drawings; and to illustrate the method by using it to differentiate between a general lunar and a general Martian mission.

We note that a requirement common to both missions and stated identically for both at a given level may, when examined by a further set of criteria, show aspects which are met in different ways for the two missions. That is, at a given level, the differences between the two missions may be stated in terms of

(1) The requirements applicable to one and not the other
(2) The differences in the ways in which the same requirement must be met for both missions.

If the breakdown is carried to a sufficiently advanced level, (2) above may be expressed in terms of (1), differences between requirements. Lacking such a breakdown, it may be profitable to establish suitable criteria and to express the differences between missions on the basis of both (1) and (2). Such an expression is qualitative, since it can only reflect stateable differences in both categories.

For the constraint of (1) above it is necessary to examine each requirement to determine whether or not it is applicable to both missions. A list of requirements applicable to one mission and not the other then helps to characterize each mission. In effect, the commonality has been reduced by the extent of the information on the list.

To accomplish the differentiation of (2) it is necessary to provide additional criteria. These may be stated in terms of

a. The site where the process involved in a requirement originates
b. The kind of information processed
c. The nature of the agency which executes the function satisfying the requirement
d. The time of execution of the function,

and characterizing each requirement at an appropriate level accordingly. Identification may then be made of the requirements which have the same description in the requirements breakdown for both missions, but which are characterized differently by the above classification. When this difference, if it exists, is expressed for each common requirement the results allow the individual missions to be described with greater uniqueness than was possible before.

In keeping with the listing above, a requirement is either

a. Space-based (SB) or earth-based (EB)
b. Current (C) or extrapolative (E)
c. Human (H) or machine (M)
d. Present (P) or future (F),

where the definitions of these terms are as follows.

- Space-based means that the information processing takes place in space (moon, planet or orbiting satellite).
- Earth-based means that the information processing takes place on earth.
- Current means that the information, when processed, reflects a known existing system state or state change.
- Extrapolative means that the information, when processed, reflects an estimated state or state change.
- Human means that information is processed predominantly by an individual or individuals.
- Machine means that information is processed predominantly by machine.
- Present means that the requirement is met by current, real-time action.
- Future means that the requirement is met by programming an action or actions to be carried out at some future time.

For purposes of clarification, a system state is defined as a set of single-parameter values associated with a corresponding set of system parameters. A change of one or more of these parameter values is a state change.

Using the criteria defined above, any desired comparison between two individual missions or between classes of missions may be made by:

(1) Examining, at an appropriate level, the requirements for each mission or class of missions for requirements applicable to one, but not the other.
(2) Examining, also at an appropriate level (not necessarily the same as that used in (1)), the requirements for differences within the same requirements as stated for both missions.
(3) Combining these differences and evaluating each of the common requirements, at the most advanced level available, for interaction with the differences. (If the requirements are now shown to differ markedly, the process may have to be iterated.)

The method stems from the need to deal with requirements as generally as possible in order to allow systems configurations to be developed which are applicable to a number of specific missions. As previously noted, if the systems requirements breakdown were carried far enough, all of the differences could ultimately be expressed as differences between requirements. Lacking this specificity, a more general assessment must be made.

For step (1), identification of common requirements, the most detailed breakdown available should be used. In the present case, this is represented by the third or fourth level. A single criterion is all that need be employed. Either a requirement is applicable to a mission (A), or it is not (N/A). Each selected requirement is then examined to determine whether or not the nature of the mission imposes additional constraints upon it.

The level which appears best suited for the purposes of step (2), characterization of common requirements, is the first level, provided, as noted before, that the paired functions are treated individually. Selection of a particular level should be made in terms of maximum usable information return for effort expended.

As an example of mission differentiation by the above methodology, a comparison is now made between the general lunar and general Martian missions.

First, each requirement as given in the Systems Requirements Breakdown outline is examined to determine whether or not it is applicable to both missions. Where differences exist, they are shown in tabular form in Table 4-2.

Table 4-2
FOURTH-LEVEL SYSTEMS REQUIREMENTS APPLICABILITY DIFFERENCES FOR GENERAL LUNAR AND GENERAL MARTIAN MISSIONS

| Fourth-Level Requirement | General Lunar Mission | General Martian Mission |
|---|---|---|
| 1.4.1.1 Wind Direction | N/A | A |
| 1.4.1.2 Wind Velocity | N/A | A |
| 1.4.1.3 Gusts (average and max.) | N/A | A |
| 1.4.2.1 Blowing Dust | N/A | A |
| 1.4.2.2 Visibility | N/A | A |
| 1.4.2.3 Cloud Coverage | N/A | A |
| 1.4.3.3 Magnetic Field Int. & Dir. | N/A | A |

Secondly, each system requirement at the first level is evaluated according to the criteria listed.

Table 4-3 shows the classification by the established criteria for the first-level functions. At this level all of the functions are applicable to both missions.

The differences between the general lunar and general Martian missions which are indicated in Table 4-3 are differences within requirements, since all of the requirements at this level are applicable to both missions. A difference arises wherever the entry in a lunar cell of Table 4-3 is different from that in the corresponding Martian cell. Preliminary statements, corresponding to these cell entries, are made below which characterize the missions accordingly.

Interpretation of Differences Shown in Table 4-3.

1. (a) Sensing of state parameters on Mars will be a space-based function. Even though a certain amount of information might perhaps be obtained by earth-based observation, it would have little value compared to similar observations made from a space-based agency.

   (b) Sensing of state parameters on the moon may be either space-based or earth-based. Either as backup modes or primary functions, certain information-collecting procedures could conceivably be carried out to advantage from the earth as well as from space. For example, the signal from an optical laser

Table 4-3
MISSION ANALYSIS, BY SITE OF RV DEPLOYMENT

| Mission | Sense | | | | Report | | | | Appraise | | | | Decide | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F |
| General Lunar | U | C | U | U | U | U | U | U | U | U | U | U | U | U | U | U |
| General Martian | SB | C | M | U | SB | U | M | U | U | U | U | U | U | U | U | U |

| Mission | Command | | | | Respond | | | | Store | | | | Retrieve | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F | SB/EB | C/E | H/M | P/F |
| General Lunar | U | U | U | U | U | U | U | U | U | U | U | U | U | U | U | U |
| General Martian | U | U | U | U | SB | U | M | U | U | U | U | U | U | U | U | U |

LEGEND

SB, EB: Space-Based or Earth-Based
C, E : Current or Extrapolative
H, M : Human or Machine
P, F : Present or Future
U : Unassigned*

*NOTE: An entry U means the function is unassignable to a specific category at this level, for any of a number of reasons (lack of information, confounding of functions, etc.).

beacon placed on the RV might be used to determine RV position, cumulative distance, and other related parameters.

2. (a) Data reporting on a Martian mission must correspondingly be space-based; data reported from earth-sensing will be too general to be of much value.
   (b) Data reporting on a lunar mission may be either earth-based or space-based. Even though the system is designed for complete automation, backup modes for executing functions such as those covered under 1. (b) above may very well be incorporated into the system.
3. (a) State sensing and reporting on Mars will be a machine function exclusively.
   (b) Both sensing of state parameters and data reporting on a lunar mission, fully automated or not, may in some cases be a human function, in others a machine function. Lunar missions will thus have more flexibility.
4. (a) Responding in the Mars case will be limited to a space agency.
   (b) Responding to commands in a lunar mission might be either space-based or earth-based, because of the large channel capacities, available power and extended periods during which the system could be operated. In a fully automated lunar mission, for example, some data might well be stored on earth and accessed by command from the RV.
5. (a) Responding in the Martian case must be exclusively a machine operation, since commands from the RV will not be sent to earth.
   (b) Responding in the lunar case might be either a machine or a human function. For example, the response in item 4. (b) above might be carried out by a human.

The above list, when augmented by the differences summarized in Table 4-2, represents the stateable difference at the first level between the general lunar and general Martian missions without taking into account that the requirements themselves might interact. A third step is therefore required to complete the analysis. Each of the requirements which had previously been examined individually is now examined in the light of the differences which were disclosed to determine if the analysis remains intact. This is done by characterizing each requirement according to the criteria and noting any new differences that arise because of differences in other requirements either in the assigned criteria or in the interpretation of the requirement. Where fourth-level requirements are not suitable, or are unavailable, earlier levels are used. The results of this evaluation are summarized in Table 4-4.

Table 4-4
EVALUATION OF GENERAL LUNAR MISSIONS AND GENERAL MARTIAN MISSIONS ON THE BASIS OF REQUIREMENTS INTERACTIONS

| Requirements | Differences Between Lunar and Martian Missions | Interactions |
|---|---|---|
| 1.2.1.2, 1.2.1.4, 1.2.3.1, 1.2.3.2 Sensing and Reporting | Outcroppings, cliffs, craters and unstable terrain may be sensed and reported from earth as well as from space in a lunar mission. In a Martian mission these must be sensed from space. | With Req. 2.1 Some appraisals and decisions regarding terrain states may be made on the basis of current earth-based data for lunar missions. For Martian missions this will not be possible.<br>With Req. 2.3 Some appraisals and decisions regarding choice of objectives, risk vs potential data return and path planning may be made on the basis of current earth-based data for lunar missions. For Martian missions this will not always be possible.<br>With Req. 3.2 Sensor operation, where such obstacles are involved, can, in some cases, be carried out on the basis of current, earth-based data for lunar missions. For Martian missions this will not be possible.<br>With Req. 3.3.2 RV drive commands may in some cases be made on the basis of current earth-based data where such obstacles are involved, in lunar missions. For Martian missions this will not be possible. |
| 1.4.1, 1.4.2, 1.4.3.3 Sensing and Reporting | Wind parameters, meteorological phenomena and magnetic field intensity and direction need not be sensed and reported for lunar missions. For Martian missions these may have to be sensed and reported. | With Req. 1.1.2 Wind pressures may affect RV control parameters and engineering parameters such as vehicle attitude, power reserves, etc.<br>With Req. 1.2.5 For all Martian missions, the presence of an atmosphere implies possibility of moisture inclusion in soil. With changing temperatures this may change soil parameters. Sensing moisture content of air and/or soil should therefore be a requirement under 1.4.2.<br>With Req. 2.1 For all Martian missions the presence of atmosphere implies possibility of sensor deterioration (corrosion, pitting due to blowing dust, etc.). Req. 2.1 should include a requirement to make appraisals and decisions regarding sensor states.<br>With Req. 3.3 For all Martian missions the presence of moisture in an atmosphere implies the freezing of drive components, etc. Req. 1.1.2 should include the capability to sense and report locked states in which received commands cannot be executed.<br>With Req. 3.3.1 For all Martian missions, since atmospheric pressure may vary, RV component pressures should be sensed and reported as part of Req. 1.1.2 and the capability to control these included in Req. 3.3.1 and 4.1. |
| 1.1.1.1 through 1.1.3.5 Reporting Only | All lunar missions can report current data. Some Martian missions must report some extrapolative data back to earth, since, because of transmission delays, states may change before the signal is received on earth. | None at this level, since the difference does not apply to all Martian missions. |

The differences between the general lunar and general Martian Missions shown by the above method are reflected in the totality of entries in Tables 4-2, 4-3, and 4-4, those in Table 4-2 arising from the criterion of applicability, those in Table 4-3 from the application of the remaining criteria as defined, and those in Table 4-4 from interaction between the requirements.

None of the above tables is complete, except in the sense that it applies to a general breakdown. As the breakdown is carried further, new interpretations of the criteria may be made, and further interactions disclosed.

The method outlined is not restricted to any given level. Its advantage is that certain conclusions may be drawn before the systems requirements breakdown has been carried out to an ultimate level. Its weakness is a loss of specificity because the ultimate levels are lacking.

The above discussion describes a methodology only. As the analysis is carried to more detailed levels it can become exceedingly complicated. For this reason, the analysis has not been carried out in detail for each of the missions of Section 3.

# 5.0 SYSTEM CONFIGURATIONS

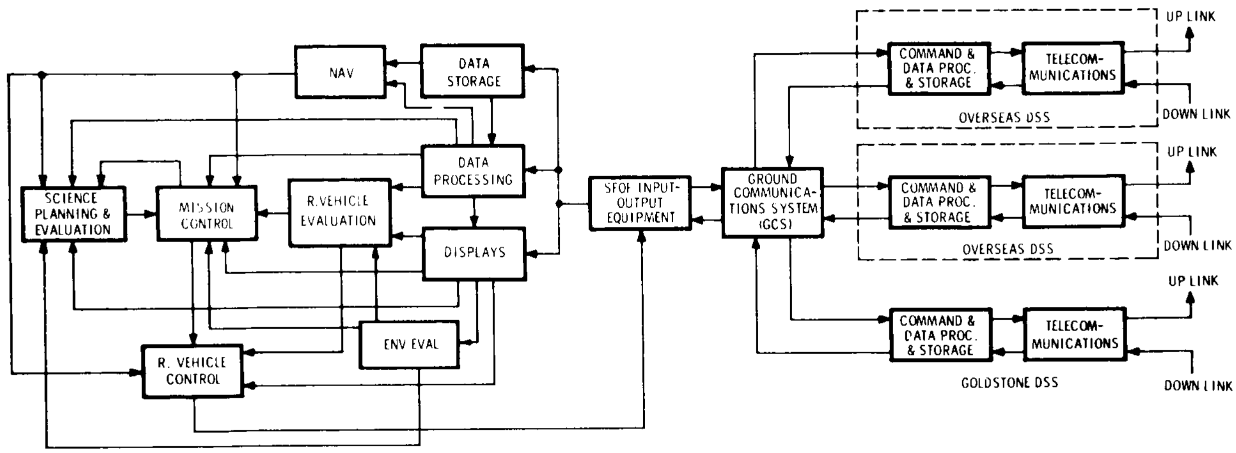
The previous section described how the six mission modes derived in Section 3 might be characterized by specifically different system requirements and by the manner in which requirements common to two or more modes might be met.

When the system requirements for these mission modes have been determined they may be used in conjunction with more general characterizations such as the degree of automaticity desired, location of individual functions, performance levels needed, system complexity permissible, etc., to build a rationale for configuring mission-specific systems. In this section the rationale for configuring systems for each mission is discussed.

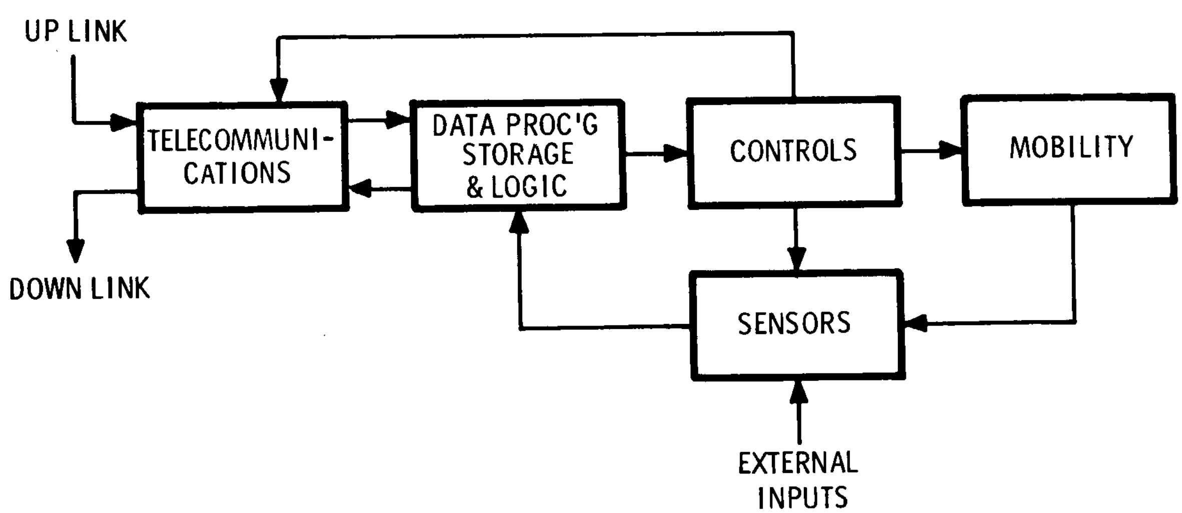
Figure 5-1 shows, in general form, the elements of any remote control system for extra-terrestrial roving vehicles. The ground-based portion, shown in Figure 5-1(a) consists of a mission operations center (SFOF), a network of transmitting and receiving stations, and an interconnecting ground communications network. One of the constraints assumed for this study is the use of the JPL Deep Space Network, and Figure 5-1(a) is based upon that constraint. It is further assumed that, as a general rule, the placement of mission-dependent personnel, equipment, or software at DSIF Deep Space Stations (DSS) is undesirable and should be avoided to the maximum extent possible. Therefore most such elements are placed at the SFOF.

At the SFOF, there will in general, be six functions: (1) Mission control, (2) Science planning and evaluation, (3) Roving vehicle and environment evaluation, (4) Roving vehicle control, (5) Data processing and display, and (6) Navigation. While any or all of these may be combined into a single person, equipment, or station, functionally they may be thought of as distinct. These functions are described in greater detail below.

The Mission Control function provides overall direction of all mission operations. This includes functions not directly related to RVMC, and in complex missions such as a Martian lander (which may involve orbital, fixed-landed, and mobile surface operations) it includes all of them. With respect to the direction of RVMC, it concerns mainly the establishment of roving vehicle objectives upon recommendation of the science planners




a) Ground-Based Equipment




b) Space-Based Equipment

Figure 5-1 RVMC General Configuration

and the ordering of suitable precautionary measures to alleviate dangerous conditions reported by Vehicle Evaluation. This function is not further broken down herein.

Science Planning and Evaluation, as the name implies, is concerned with the scientific aspects of the mission, and may also include functions not directly related to RVMC. Since it is assumed that the overall objective of any mission is scientific in nature, this function is of cardinal importance to the overall mission operation, and is therefore shown in relation to other functions for completeness. It likewise is not developed in greater detail herein, since it does not play a central role in the RVMC operation.

Vehicle Evaluation is concerned with the present state of the vehicle and its subsystems. This function involves monitoring on-board temperatures, voltages, currents, pressures, state of charge, conditions of operation, and other variables indicative of or affecting the operation of the vehicle itself, as well as reporting internal conditions which threaten the future effectiveness of the roving vehicle system. A concomitant function is Environment Evaluation which is responsible for being continuously aware of external conditions, slopes, obstacles, soft soil conditions, sun glare, dust or wind storms, ambient temperature conditions, etc., which endanger the vehicle or any of its subsystems, and for recommending appropriate precautionary measures. In performing these evaluations, use is made of both real-time and delayed displays of incoming data related to vehicle status, and processed data. In addition, appropriate stored data representing events of the past may be recalled as needed.

Vehicle Control must formulate a plan for achieving the objectives defined by mission control and, as appropriate to the level of automaticity involved, must formulate the commands and command sequences to execute that plan. It must also provide for reprogramming of on-board decision processes, where applicable, on the basis of past performance and present conditions as reported by vehicle evaluation.

The SFOF is connected with the transmitting and receiving stations of the Deep Space Instrumentation Facility (DSIF) through the Ground Communications System (GCS). The GCS is assumed to be equivalent to that described in Reference 6. The GCS does not provide capacity for routine data transmission from overseas sites to SFOF at rates which are likely to be realized between the moon and earth, and perhaps not even those achievable from Mars. The use of overseas transmitting and receiving stations will be affected by this limitation and, in some instances, may be ruled out entirely as far as motion control is concerned. Therefore, these sites are enclosed in a dotted line on Figure 5-1(a), indicating that in some configurations they may not be part of the RVMC system.

At each Deep Space Station (DSS) there is a data processing and storage function which processes outbound commands, programming instructions, etc., and inbound telemetry. At these stations there is also a telecommunications function consisting of transmitters, receivers, antennas, and their associated equipment.

The space-based portion of the system, shown in general form in Figure 5-1(b), consists of the telecommunications equipment forming the other end of the RF link, data processing, storage and logic functions, sensors, controls, and the mobility subsystem, control of which is the ultimate objective of the RVMC system. There must, of course, also be a power subsystem which, while not an element of the control loop itself, must nevertheless be considered in tradeoff analyses involving information transfer rates and mobility under weight and/or volume constraints. Controls are generally applied not only to the mobility subsystem, but to many of the sensors and to the telecommunication system, particularly the antenna.

## 5.1 CONFIGURATIONS FOR THE THREE MISSION MODES

Starting from this general RVMC system configuration and the detailed system requirements defined in Section 4, generalized configurations were evolved for each of the three modes of operation. These configurations conveniently break down into SFOF-based, DSIF/GCS, and space-based portions. These system configurations are about as detailed as possible while still retaining a great degree of generality with respect to each mode.

In many cases, the system requirements could (conceptually, at least) be met in a variety of ways. Rather than attempting to generalize to include all possible concepts, engineering judgment was used to eliminate some which were clearly inferior and those which violated some ground rule of the study. For example, no system is considered which depends upon relay communication through either a lander or an orbiter. Lander relays were eliminated by the ground rule requiring that no system be inherently range-limited. Orbiter relays were eliminated as a prime mode on the basis of availability and reliability, although they might be considered as a backup.

## 5.2 DSIF CONFIGURATION

As a direct result of the desire to avoid placing mission-dependent elements at DSIF sites, the general configuration of the DSIF sites is identical for all three modes. Figure 5-2 shows this general configuration. At each site, up-bound commands are routed through a command processor to the transmitter. The command processor also performs the function of command verification and, if commands are not verified, it inhibits transmission of the command and notifies the operations center (SFOF). (The word "command" is here used to include such things as roving vehicle destination coordinates, computation instructions, addresses, path plan data, etc., when applicable.)

All up-link traffic is assumed to be transmitted on the 210-foot antennas at Goldstone, Madrid, and Canberra, while down-link data reception may be on either or both the 210- and 85-foot dishes, divided on the basis of data rate, operational importance, permissible error rates, and perhaps operating costs. All data received are recorded, and active operational control data are processed in the telemetry data processor and transmitted to SFOF.

As noted above, the use of overseas sites is affected by data rate limitations in the GCS. In some cases, where incoming data rates are expected to exceed GCS capabilities at the overseas sites for short intervals or only for certain kinds of data, it might be appropriate to use some form of data compression at these sites, particularly where the compression techniques would not require mission-dependent equipment. Therefore, for generality, data compression is shown in Figure 5-2 at the Madrid and Canberra sites, but not at Goldstone where the wide-band microwave link to SFOF should be capable of handling any anticipated data rate requirements.

In the case of lunar missions, the anticipated data rates are significantly higher than projected overseas GCS capabilities so that the GCS could become a major operational bottleneck. One way around this problem is to duplicate much of the operations control center capability at the overseas sites, but this does not appear practicable. Therefore, it seems quite likely that lunar missions which require considerable telecommunications traffic would be conducted almost entirely through the Goldstone site, with overseas sites used mainly for monitoring the vehicle status during nonoperational periods, and perhaps for collecting low-data-rate scientific data.

The capabilities of the GCS anticipated by 1973 will probably not be severely taxed by either up-link or down-link control traffic in the case of Mars, although a detailed

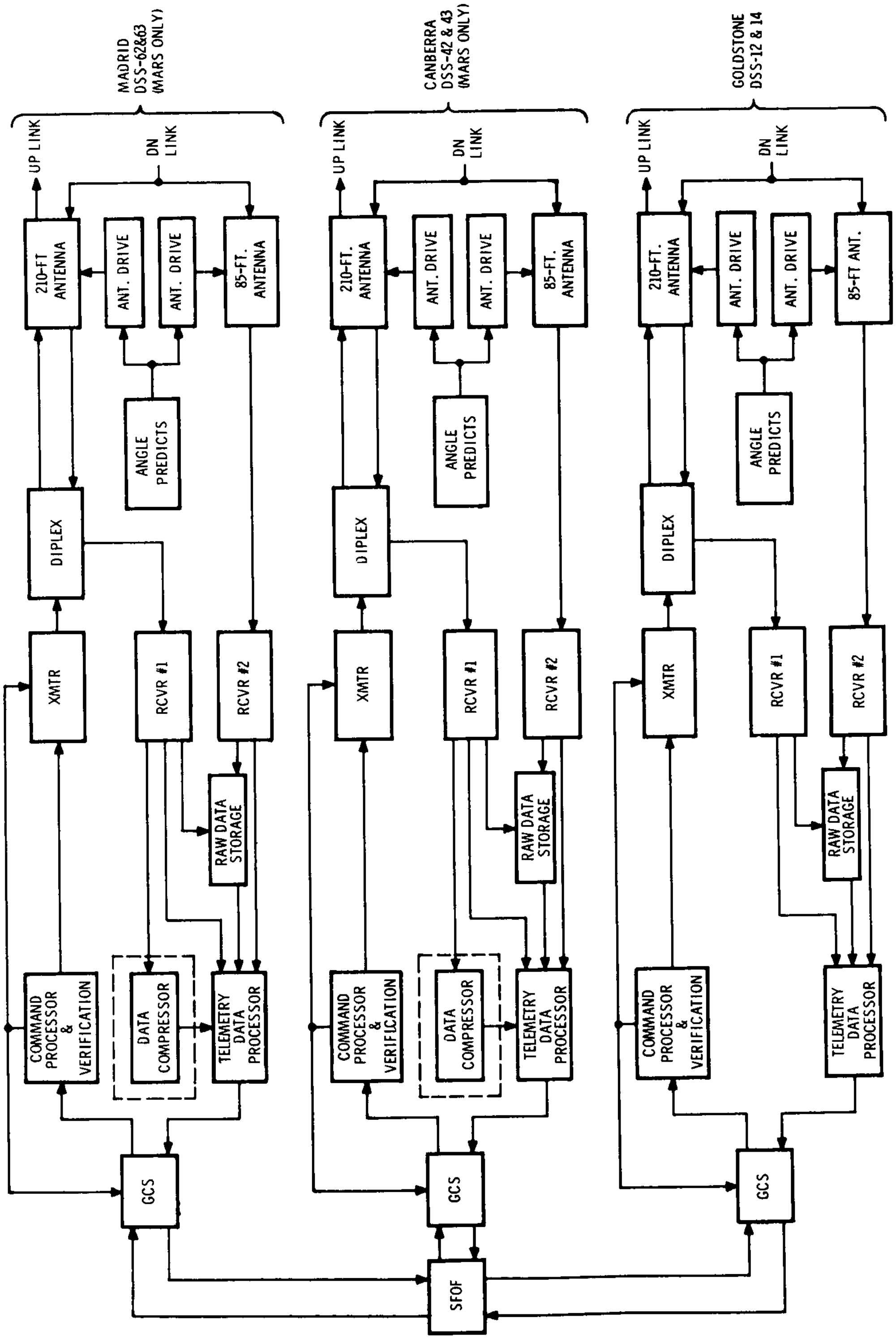



Figure 5-2 DSIF/GCS Configuration

operations analysis should be performed to determine what limitations, if any, are imposed by the GCS. Although it is conceivable that Mars-Earth data rates could, at times, saturate the 4800-bps high-speed data lines between overseas DSIF sites and SFOF, they are unlikely to exceed GCS capability by more than a factor of two or three because of power-gain limitations on the vehicle. This can be handled either by transmitting data to SFOF through buffer storage at a rate slower than received at the DSIF, if this happens only occasionally, or by using some data compression technique at the DSIF site, or by a suitable combination of the two. Although most forms of data compression are best accomplished as close to the data source as possible, many forms depend upon high signal-to-noise ratio to realize maximum advantage, and many forms entail some loss of information. Thus, if data compression is, in fact, needed because of GCS limitations, it might be advantageous to accomplish it at the DSIF site after recording and with potentially high S/N, in the subsequent transmission channels.

In the Martian case, therefore, the use of overseas sites is warranted. Indeed, because of the rotation of both Mars and the earth, it is necessary in all Martian cases to use overseas DSIF sites during surface operations to assure a reasonable operating window for communications. Although this may sometimes impose data rate restrictions that could slow down operations, as noted above, the alternative use of Goldstone only could result in communications windows frequently approaching zero for large areas of Martian surface and, therefore, vastly reduced overall data flow. Accordingly, the use of DSIF sites at Goldstone, Canberra, and Madrid, is assumed for Martian missions. Each of these sites is to be equipped with both 85-foot and 210-foot-diameter antennas after 1971.

In the following sections the SFOF-based and space-based portions of the systems configurations are discussed for each of the three modes – fly-by-wire, semi-automatic, and fully automatic.

## 5.3 FLY-BY-WIRE MODE

### 5.3.1 SFOF-Based Configuration

In the fly-by-wire mode, all control decisions are made at the operations control center and all commands emanate from this center except those for which the safety of the vehicle requires a reaction time shorter than that allowed by the system and the applicable constraints. Basically this means that the only decisions made on board the vehicle are those which stop the vehicle because of the occurrence of a physical condition which poses an immediate threat, such as tilt or loss of a wheel contact.

The operations control center, shown in Figure 5-3, consists of several levels of control as discussed above. Mission Control, having overriding control of all aspects of the mission, receives advice on scientific objectives from Science Planning and Evaluation and current data on the status of the RV system from RV Evaluation. The Mission Controller is kept constantly aware of RV position by means of a navigational display, and is aided in establishing objectives by a continuously updated terrain model (discussed below). On the basis of these inputs, Mission Control establishes a long-range objective (LRO) which is perhaps tens or hundreds of vehicle lengths from the present position. Alternatively, he might demand a prearranged search pattern or some other objective.

In response to this objective, and with the use of the terrain model, the path planner establishes a sequence of intermediate and/or short-range objectives (IRO and SRO) which define the path to be taken to achieve the LRO. This path plan is formulated on the basis of a knowledge of vehicle capabilities relative to the local terrain features as defined by the terrain model. Since these will not generally be known in detail, a lower level of control is embodied in the RV Controller, who issues all detailed start, stop, and steering commands as well as commands needed to control the RV sensors.

When terrain conditions permit, the RV Controller may choose to transmit a sequence of commands, rather than resorting to a one-command-at-a-time mode. To illustrate this alternative, a Command Sequence Generator is shown, although this may not be a separate piece of equipment.

Time permitting, all mobility commands issued by the RV Controller are subject to review by RV Evaluation to assure that they will not endanger the vehicle. No command is transmitted to the GCS without such safety clearance.

All incoming data are stored as received, and processed in a central decoder before being routed to users. Current environmental data, engineering parameters, roving vehicle attitude and proximate terrain data, are fed directly to Roving Vehicle Evaluation. As described below, terrain sensors on the roving vehicle are categorized as short-range or long-range. The data from the latter are appropriately processed to meet the particular needs of each user and are stored for call-up on demand. These

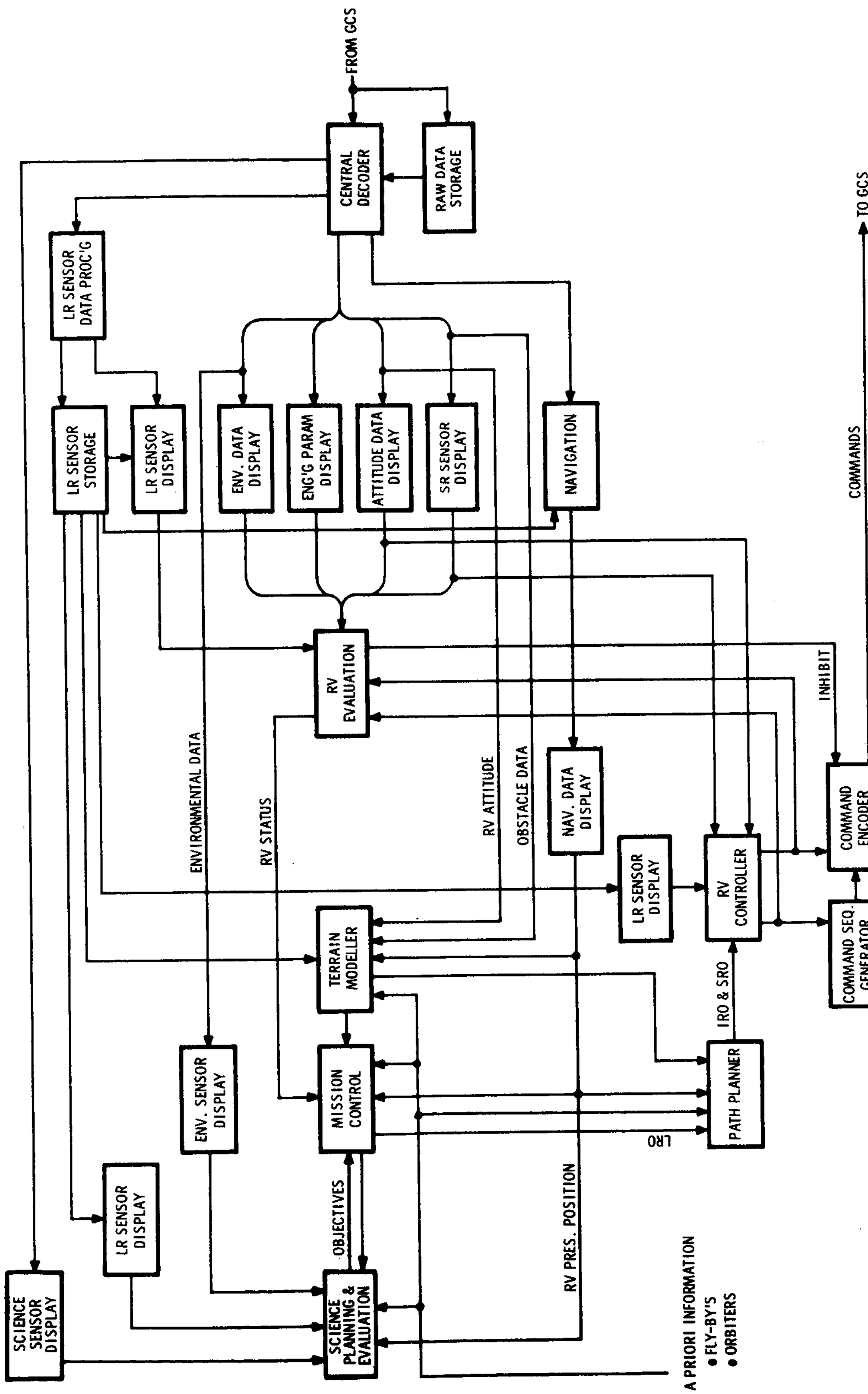



Figure 5-3 Fly-By-Wire Configuration, SFOF-Based Equipment

data are used for various purposes for Science Planning and Evaluation, Roving Vehicle Evaluation, and for the updating of the Terrain Model. Science Planning and Evaluation also uses environmental data, while raw navigational data and long-range sensor information are fed to a navigation station to get present position which is displayed to Science Planning, Mission Control, and the Path Planner, and is used in Terrain Modeling.

To assist all earth-based functions, but primarily path planning, a terrain modeller is envisioned. This assimilates all available data concerning the nature of the surface in the area of interest. These data are used to provide a model which represents a "best estimate" of terrain conditions and which is continually updated as further data are obtained. The model should also provide a measure of the confidence in the estimate. Such a model might well be started prior to launch through the use of pictures taken on fly-by missions such as Mariner 4 or Lunar Orbiter. Pictures from orbiting and landing spacecraft may provide a level of improvement in the model prior to the start of actual roving vehicle exploration. As the roving vehicle moves out from the landing site, its own sensors provide a further improvement in both the level of detail of the model and the confidence in the estimate. Also, correlation of vehicle-derived terrain data with wide-area data such as those derived from orbiters will probably permit extrapolation of the model in unexplored regions to levels of greater detail with improved confidence. This, in turn, should assist the Science Planning Staff in the choice of interesting new destinations and the Path Planner in choosing preferred paths with greater confidence. It might also provide the means for improving on-board preprogrammed decision processes which are at least partly based upon terrain statistics.

The actual implementation of the terrain modeller will probably involve a rather intimate man-computer-display interface. As such, it might be patterned after any of several computer-assisted design systems (e.g., the General Motors DAC-1 System). Several important potential differences can be conceived, however. For example, it might be quite sufficient from the vehicle motion control standpoint to represent mobility hazards symbolically, or in outline only, rather than to generate a mathematical model and a display of the actual surface. Also, as noted above, it would seem to be quite desirable to provide statistical measures of confidence on the location, the number, and the size of mobility hazards plotted, so that the RV controller would have some measure of control latitude open to him, as well as the relative desirability of two symbolically similar routes. The means to do this could well be the basis of a separate study.

In order to accomplish the navigation function, data which can be readily handled by computer (values associated with dead reckoning, angle of terrain incline, etc.) will be processed automatically. These data may be corrected by references established by photo-interpretation, involving such considerations as views of the same object from different stations, study of vehicle tracks and, where applicable, correlation between vehicle-returned data and orbiter photographs.

### 5.3.2 Space-Based Configuration

The space-based portion of the fly-by-wire configuration, shown in Figure 5-4, consists for the most part, of sensors and controls together with the on-board telecommunications equipment needed to transmit data and commands between the earth and the roving vehicle.

Based on the ground rules of the RVMC study, it is assumed that the space-based roving vehicle control functions are integral with the vehicle itself, i.e., no communication relay is made through either the lander or an orbiting spacecraft. This does not mean to eliminate the use of orbiter pictures in the guidance, however.

The sensors are classified into eight separate categories, seven of which are explicitly shown in Figure 5-4. These are as follows:

1. Vehicle engineering parameter sensors – sensors which monitor the engineering quantities of vehicle performance, e.g., temperatures, pressures, voltage, etc.
2. Navigation sensors – sensors which measure quantities used to determine position with respect to some reference coordinate system.
3. Control sensors (not shown) – sensors which measure the state of any controlled quantity for purposes of comparison with command reference inputs.
4. Short-range terrain sensors – sensors which detect actual physical encounter with mobility hazards.
5. Long-range terrain sensors – sensors which are capable of detecting mobility hazards at some distance from the vehicle, generally a few vehicle lengths or more.
6. Attitude sensors – sensors which measure the angular orientation of the roving vehicle with respect to a local coordinate system.
7. Environmental sensors – sensors which measure environmental variables affecting vehicle control in some manner.

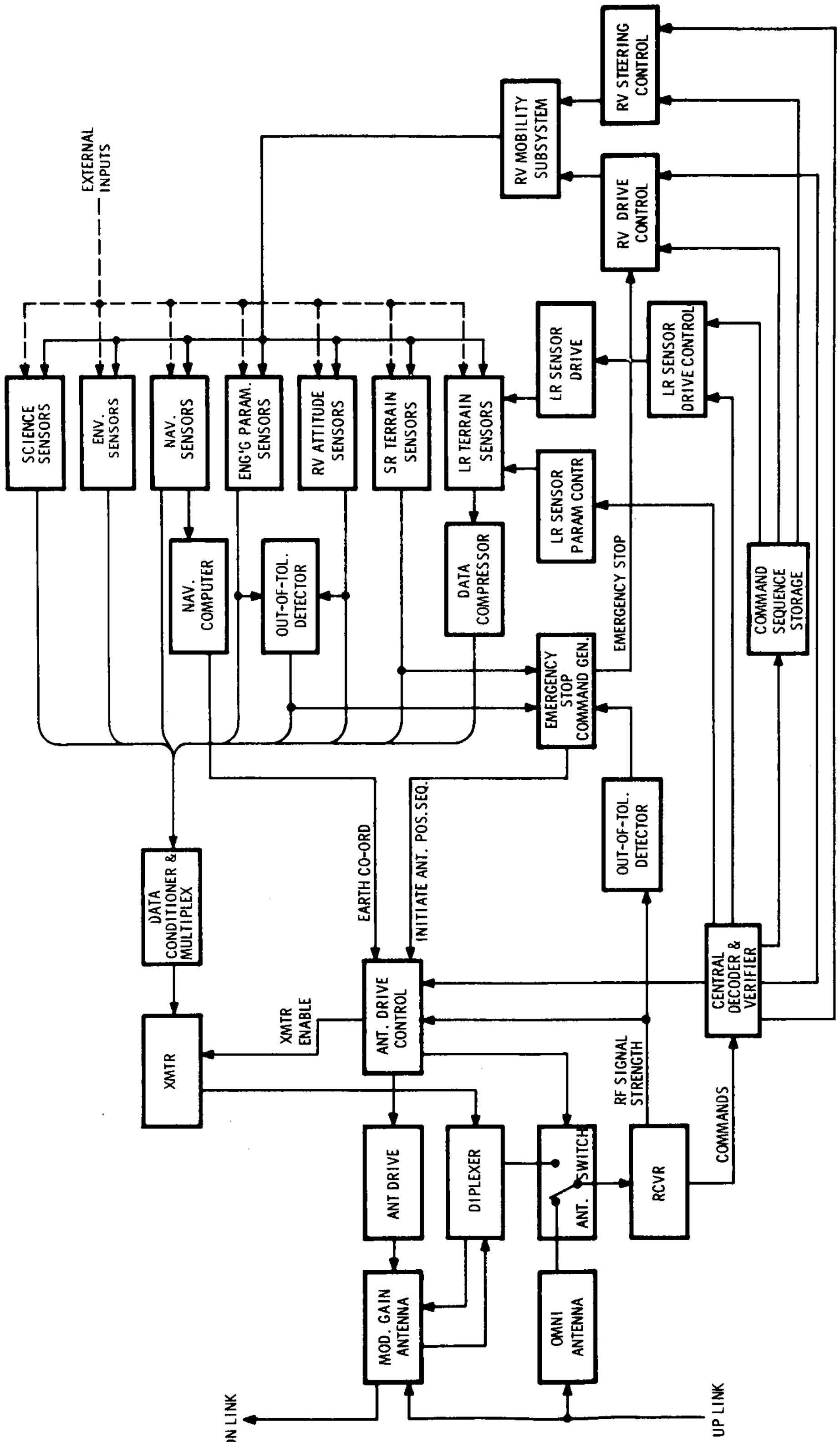



Figure 5-4 Fly-By-Wire Configuration, Space-Based Equipment

8. Science sensors – sensors which gather scientific data to carry out the mission scientific objectives.

Vehicle engineering parameter sensors play no direct role in control of the roving vehicle, except possibly to initiate a STOP command or corrective action sequence whenever a sensed variable (or function thereof) falls outside some preprogrammed tolerance limits. The action to be taken and the related commands depend upon which variable is out of tolerance, and may also depend upon the amount and/or direction of the out-of-tolerance condition. An out-of-tolerance condition is transmitted to earth, and in some cases may also be transmitted to an emergency STOP Command Generator which automatically stops motion when system time delays would otherwise be too great for vehicle safety.

Navigation sensors generally do not directly sense those navigational quantities of interest but instead measure quantities from which the others may be derived. The existence of some sort of navigation computer is implied. For the fly-by-wire configuration this computer will normally be on the earth, since the basic philosophy of this configuration is to maintain maximum simplicity of the space-based equipment. There is, however, a possible need for some navigational computation, expecially in the Martian case, to assist in orienting the directional antenna, as will be discussed below. The nature of this computer depends upon the type of navigation scheme adopted.

Control sensors provide a means of confirming the execution of control actions in accordance with control commands. They sense antenna position, steering angles, sensor orientation (especially of the long-range sensors), controlled sensor parameters, and, if appropriate, drive and brake conditions.

Short-range sensors include miscellaneous switches or switch actuators, devices to measure soil properties, and possibly tactile arms, feelers, etc., which may be used to measure sizes of objects.

Long-range sensors include a wide variety of devices having very diverse characteristics and requiring widely different approaches to assimilation of their outputs. They are categorized by their ability to gather information about the mobility environment through means other than direct contact. This will generally involve reception of electromagnetic energy in some portion of the spectrum, either passively or by means of reflection of energy emitted from the vehicle. In some cases it might be possible to conceive the use of acoustic energy for this purpose, but the application of such an approach is not clear at this time.

Long-range sensors include imaging systems such as television or facsimile which inherently have a high bit content and great amounts of redundancy. Anticipating that this will, in some cases, tax the capabilities of the RF link, a data compressor is shown at the long-range sensor output. Long-range sensors, in general, also require orientation and may have controllable parameters. For these functions a sensor parameter control and a sensor drive control are shown in Figure 5-4.

Attitude sensors are concerned primarily with determining the orientation of the roving vehicle with respect to the local gravity vector to prevent overturning and perhaps to assist in the assimilation of other sensor outputs, e.g., long-range sensors. In the case of articulated vehicles, each unit may require such sensors.

Environmental sensors and science sensors play no direct role in the control function but are only included in Figure 5-4 for completeness.

In the fly-by-wire configuration, sensor data are fed directly into the telecommunication channel through a Data Conditioner and Multiplexer. Down-link transmission is accomplished through use of a moderate gain (perhaps 20 to 30 dB) antenna, although from the moon narrow-band data might be transmitted on an omni-directional antenna. Transmission may be initiated either automatically by an emergency STOP command arising from an out-of-tolerance condition, or upon command from earth.

So that commands from earth may be received at all times, an omni-directional antenna is provided. Upon reception of a command to orient the antenna, coarse positioning of the antenna begins, using coordinates supplied by the navigation computer. When the antenna is positioned so that signal reception can occur on the directional antenna, an antenna switch is actuated and the antenna drives are actuated to maximize received RF signal strength. Until this action has taken place, the transmitter is prevented from operating by a disabling circuit from the antenna drive control. RF signal strength is also monitored during motion of the vehicle and causes an emergency STOP command whenever it becomes weak, indicating occulting of the earth by some local terrain feature.

Commands are decoded and verified and sent directly to the controls. In the event that the terrain permits command sequences to be sent, the system provides storage capability for these sequences.

The ability to transmit narrow-band data to and from the moon on an omni-directional antenna makes it possible to eliminate the navigation computer on lunar configurations. The raw navigational data could be transmitted to earth where the antenna pointing coordinates could be computed. Of course, on the moon, the disc of the earth is large enough and often bright enough that it might be sensed directly to get antenna position.

## 5.4 SEMIAUTOMATIC MODE

### 5.4.1 SFOF-Based Configuration

Consistent with the placement of decision making capability on board the roving vehicle in the semiautomatic mode, the ground-based complex tends to be somewhat simpler. In particular, the RV Controller function is moved to the roving vehicle and the related displays are eliminated. The semiautomatic SFOF-based configuration is illustrated in Figure 5-5.

Roving Vehicle Control in this case consists mainly of path planning, which is accomplished using both the a priori information and the updated terrain model. Once the general route is mapped out, a sequence of interim navigational goals is transmitted to the roving vehicle for storage. These goals are transmitted through the Command Sequence Generator. In addition to the interim navigational goals specified by the path planner, the command sequence generator handles all requests for readout of stored data from the roving vehicle sensor storage. In a degraded mode of operation, or under special terrain conditions or mission requirements, the Command Sequence Generator also assumes the role of generating sequences of detailed step-by-step steering and drive commands, as in the fly-by-wire mode.

Parameter values specifying the present position of the roving vehicle must be available on the vehicle itself, thereby requiring a full navigation computer capability there. This requirement thus eliminates the computer on earth.

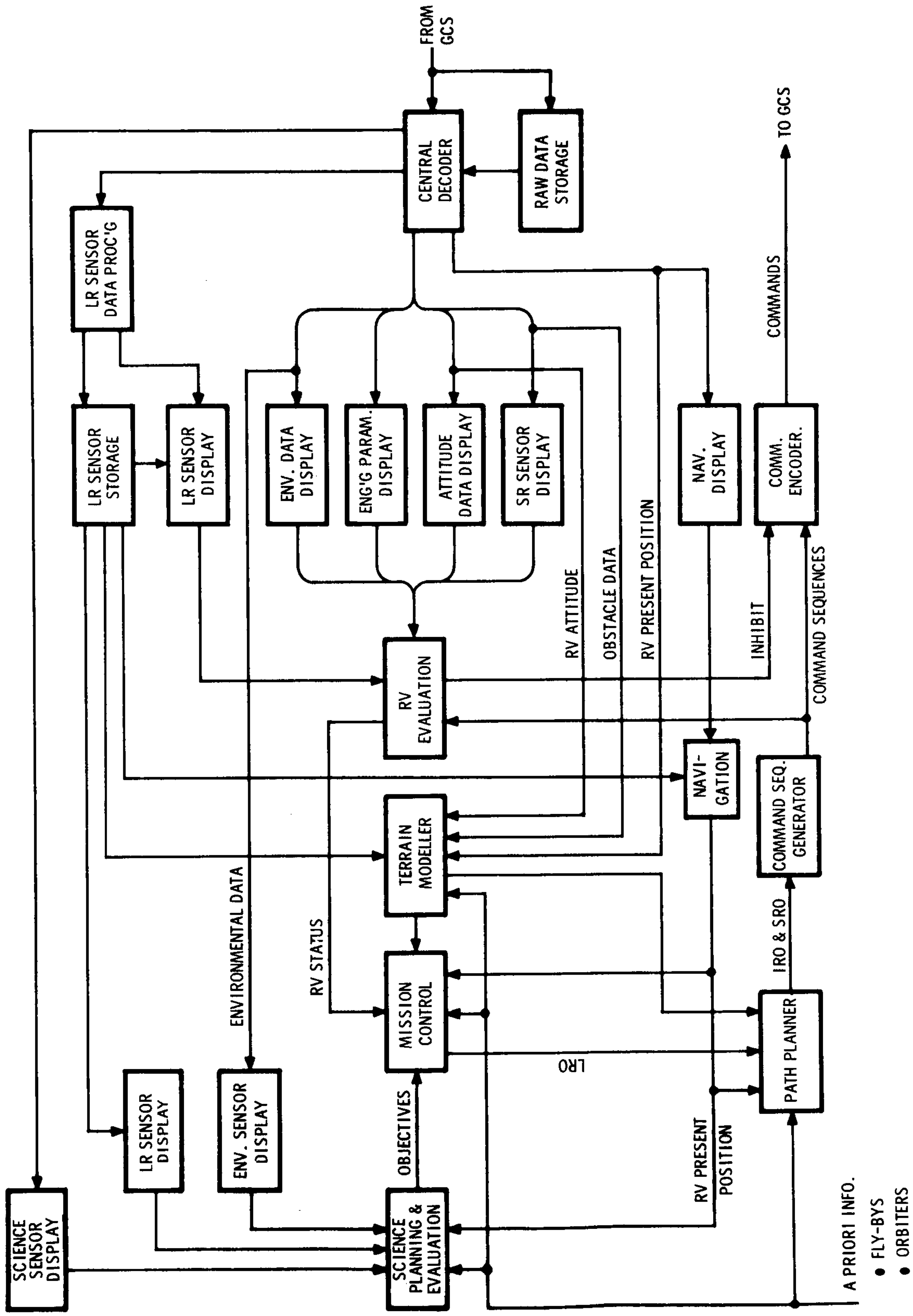



Figure 5-5 Semiautomatic Configuration, SFOF-Based Equipment

### 5.4.2 Space-Based Configuration

The space-based portion of the semiautomatic configuration is shown in Figure 5-6. The core of this configuration is the Master Control Logic. Here are stored all computational algorithms, control strategies, and destination descriptors. Raw and processed sensed data are acted upon in the Master Control Logic to produce control signals which start, stop, back up, and steer the vehicle, as well as control signals which operate certain of the sensors. (The Master Control Logic is not necessarily a single physical module, but rather a basic functional block.)

In this system, data are not transmitted continually to earth, but only when "significant" control information is acquired, or when an automatic STOP command is issued, or upon special command from earth. Normally, control commands are generated within the Master Control Logic in response to data which originate with the on-board sensors or are inserted ahead of time by earth sources. Sensor data are stored on board. In some cases a continuous time recording may be made until readout occurs. In other cases only the latest values will be stored.

As noted above, the navigation computer for determination of present position is placed on the roving vehicle. The outputs of this computer are compared with the destination coordinates in the Master Control Logic. Mechanization of this computer is, of course, strongly dependent on the choice of sensors and the performance level desired. The navigation computer also provides coarse positioning data for the antenna, as in the fly-by-wire mode.

Sensor outputs which are used in the on-board control function are fed to the Master Control Logic (either directly, or appropriately processed as in the navigation computer and out-of-tolerance detectors). The Master Control Logic then, in accordance with its stored decision algorithms, generates appropriate control commands to move the vehicle in a manner which will safely achieve the navigational goal, or to gather additional data if needed to reach appropriate control decisions. The latter function may involve orientation of long-range sensors and/or variation of long-range sensor parameters.

After any STOP command is issued, the antenna is automatically oriented in accordance with data from the navigation computer, and is ultimately finely oriented by locking onto and tracking a beacon signal from earth. Alternatively, for lunar missions this might

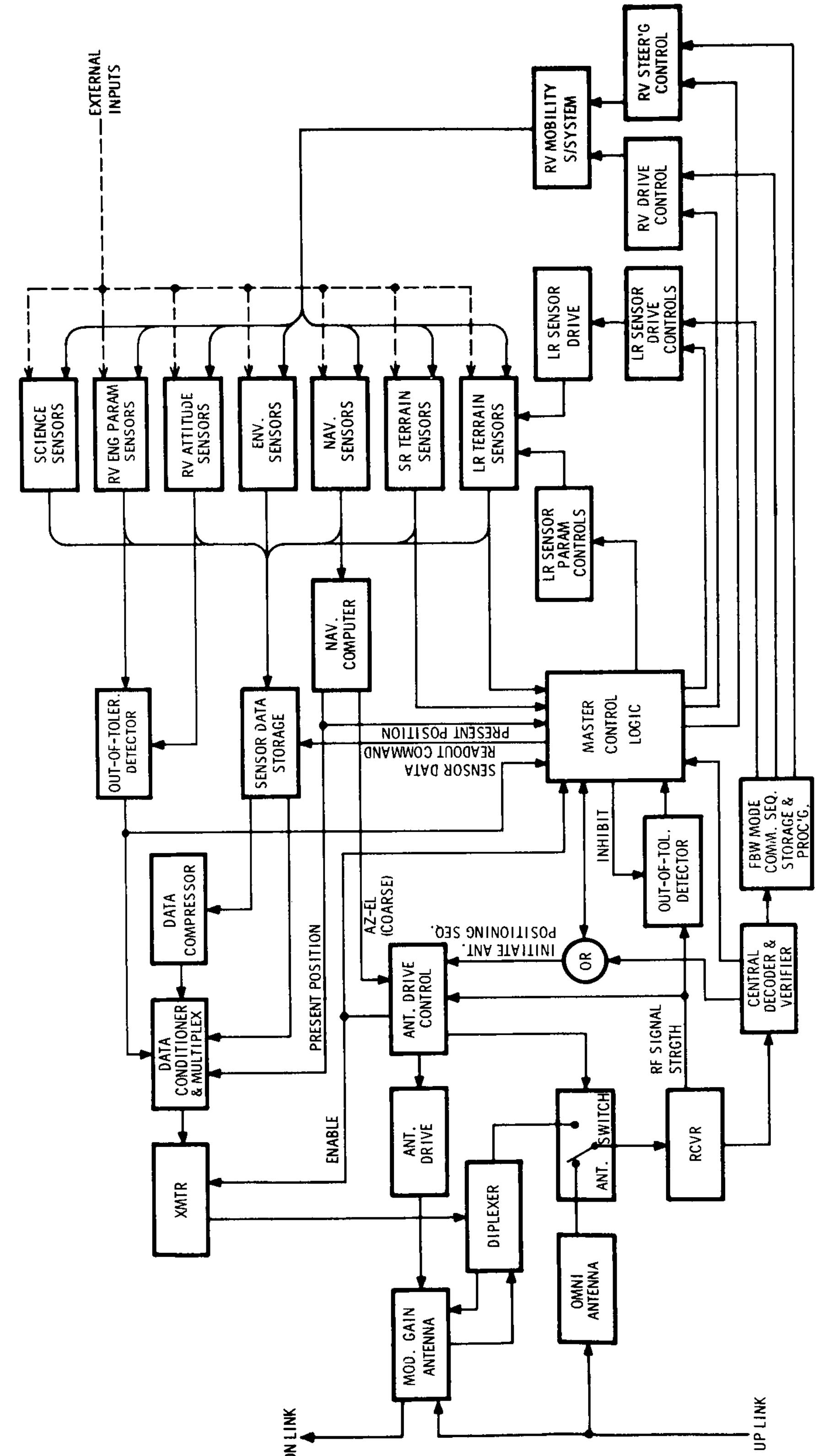



Figure 5-6 Semiautomatic Configuration, Space-Based Equipment

be accomplished by an earth-seeking sensor, as noted in Section 5.3. Selected sensor data are then automatically read out of storage, appropriately conditioned, and transmitted to earth. Data compression is shown as a possible additional feature. After automatic readout of these data the roving vehicle rests while awaiting further instructions from earth.

As with the fly-by-wire mode, data transmission is accomplished through an orientable, moderate-gain antenna providing a direct link with the three 210-foot DSIF antennas. Up-link control traffic normally consists of the location coordinates of navigation goals, reprogramming of on-board stored decision processes, and any special commands to read out stored sensor data that are not automatically transmitted. As a backup mode, with degraded performance, or for certain short-term special requirements, the up link can also carry detailed steering, drive, and sensor control commands normally generated on the vehicle.

Down-link traffic normally consists of the values of specified subsystem or system state parameters at the time of execution of any STOP command, and indications of an out-of-tolerance condition for any tolerance-limited variable. Also, stored sensor data are read out on command from earth and additional sensor readings are made and transmitted if and when required.

After the automatically transmitted data are assimilated and evaluated at earth, any of several courses of action may be undertaken upon command from earth.

1. A new destination and path plan may be inserted.
2. Additional sensor data may be requested.
3. A fly-by-wire mode may be entered.
4. Scientific experiments may be undertaken.
5. Special command sequences may be transmitted to alleviate a troublesome control situation.

### 5.4.3 Master Control Logic

Figure 5-7 shows conceptually what is contained in the Master Control Logic function. Inputs originate from four sources: sensors used directly in the control function, earth commands, the navigation computer, and the transmitter.

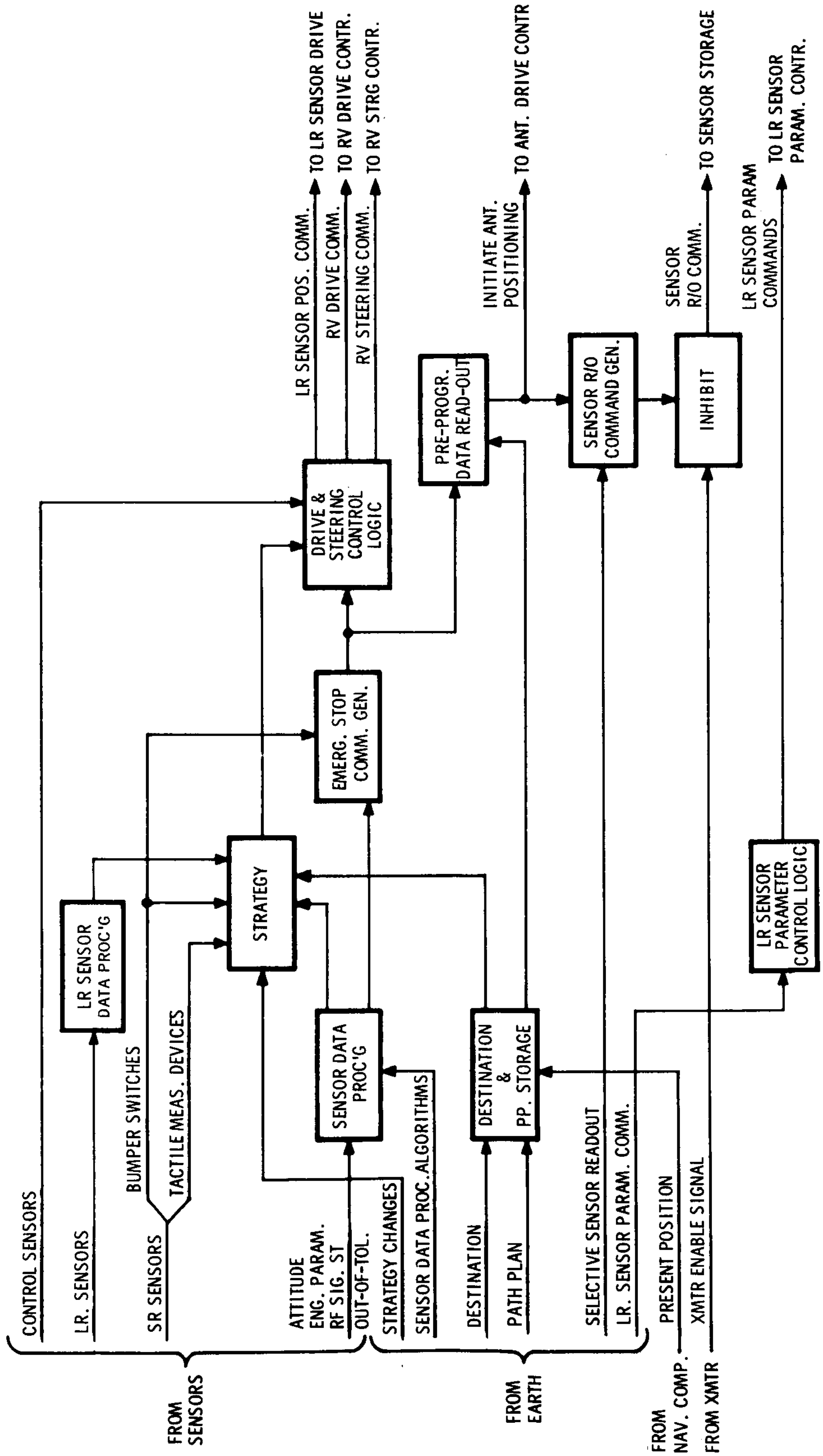



Figure 5-7 Semiautomatic Configuration, Master Control Logic

As noted above, long-range sensors include imaging systems such as television or facsimile, as well as pulse ranging systems using lasers or radar techniques and radiometers. The use of such sensors implies a concomitant ability to assimilate their outputs to appraise the significance of the data so acquired, and to make valid control decisions based thereon. Although this is clearly true of any sensor, it becomes a much more complex matter in the case of the majority of long-range sensors which might be considered. Thus, one must evaluate not only the usefulness of the type of data acquired by a given long-range sensor, but the means which are required to realize that usefulness. This is discussed more fully in Section 6. Whatever form the long-range sensors take, one of the most difficult portions of the Master Control Logic to implement appears to be the LR Sensor Data Processing function.

Sensor data, appropriately processed, are inputted to a stored strategy which, in effect, is a set of preprogrammed responses to various possible conditions that might arise. (One such response will, of course, be to stop the vehicle and await further instructions because the sensor data indicate a situation with which the stored strategy is unable to cope.)

Actions formulated by the stored strategy are transmitted to the Drive and Steering Control Logic, resulting in the appropriate drive and steering control signals to carry out the action. Consistent with the strategy and subject to override by the emergency STOP command generator, this function generates drive and steering control signals to follow the stored path plan transmitted from earth.

Upon issuance of an emergency STOP command, the antenna is automatically oriented, and selected stored sensor data are automatically read out of storage.

## 5.5 FULLY AUTOMATIC MODE

### 5.5.1 SFOF-Based Configuration

In the fully automatic mode, the ground-based operational equipment looks much like that for the semiautomatic mode shown in Figure 5-5. The major difference is the removal of the path planning function to the space-based Master Control Logic. This, in turn, eliminates the Command Sequence Generator as an element of the basic system. The SFOF-based complex assumes a monitoring role. Of course, it is desirable that the fully automatic system be capable of operating in the semiautomatic or even fly-by-wire mode, so that these functions are not completely eliminated but are relegated to a backup status.

It is likely that initial programming of a fully automatic system will be based on incomplete information about the environment. Therefore, one of the chief functions of the ground-based operation is to observe the efficiency with which automatic control of the vehicle is carried out and to reprogram the control processes when this would improve effectiveness.

### 5.5.2 Space-Based Configuration

At the level of detail described in this section the space-based configuration of the fully automatic system, shown in Figure 5-8, is quite similar to that of the semiautomatic.

The major differences will be in the Master Control Logic, which must be substantially more sophisticated for the fully automatic system. At the present stage of the RVMC study no means of implementing this capability have been worked out, but it would appear to be a very fruitful place to consider the possibility of adaptive and learning control techniques. Such techniques, at least for this kind of application, are in very early stages of development but show considerable promise where the control problem itself has been clearly defined. Within the Master Control Logic, these techniques would seem to be particularly applicable to the generation of a strategy which evolves as the mission proceeds.

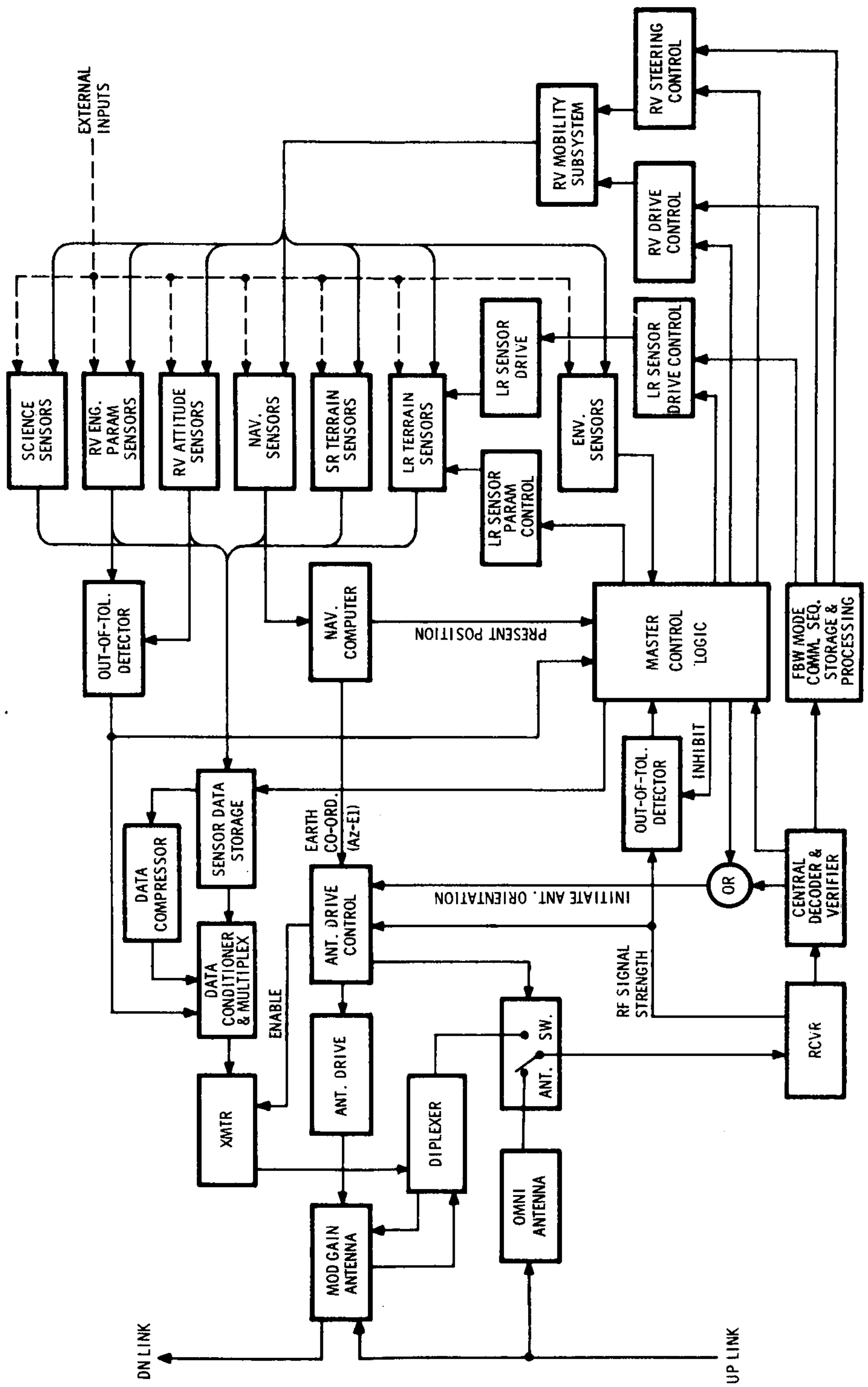



Figure 5-8 Fully Automatic Configuration, Space-Based Equipment

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# 6.0 SUBSYSTEM IMPLEMENTATION AND STATE OF THE ART

## 6.1 SENSOR SUBSYSTEM

### 6.1.1 Sensor Subsystem Performance Requirements and Parameters

For vehicle control it is necessary to gain certain information concerning the vehicle and its surroundings from which control decisions can be made. The required information is independent of hardware choices and sensor subsystem configurations and therefore must be considered first. The quantities to be determined, are listed in Section 4.3. These are:

- Roving vehicle internal states
- Surrounding terrain states
- Navigation parameters
- Environmental states

Tables 6-1, 6-2, 6-3, and 6-4 list quantities which may have to be determined under each of these classifications and the basic parameters involved.

In order to choose system configurations and hardware, depending on mission requirements, terrain types and constraints, one must determine which quantities can be sensed directly and those which cannot. In general, this will often determine the degree of possible automaticity at the present level of development of artificial intelligence. In Tables 6-1 and 6-3 all quantities can be directly measured. In Tables 6-2 and 6-4 all quantities can be measured directly or indirectly. Hardware to do it either way is discussed in Section 6.1.3 together with the relative merits.

### 6.1.2 Sensor Subsystem Basic Configurations

Mechanization of the sensor subsystem is relatively straightforward for determination of those quantities listed in the previous section as being measurable directly. This section will consider the factors which are involved in choosing between direct and indirect methods of measuring control quantities for decision-making by man or machine. As listed in the previous section, the two areas of terrain assessment and determination of navigation parameters can be handled (in theory at least) by either direct or indirect methods.

Table 6-1
BASIC PARAMETERS FOR ROVING VEHICLE STATES

| Quantity to be Determined | Basic Parameters | Direct Measurement | Indirect Measurement |
|---|---|---|---|
| RV Attitude<br>With respect to local vertical | Roll and pitch operating range<br>Measurement accuracy<br>Sampling rate | x | |
| RV Attitude<br>With respect to horizontal reference | Roll operating range<br>Pitch operating range<br>Measurement accuracy<br>Sampling rate | x | x |
| RV Attitude<br>With respect to astronomical bodies | Roll and pitch operating range<br>Measurement accuracy<br>Sampling rate | x | x |
| Temperature<br>Motors<br>Compartments<br>Sensors<br>Battery<br>RTG | Operating range<br>Measurement accuracy<br>Sampling rate | x | |
| Electrical<br>Power<br>Current<br>Voltage | | x | |
| Force & Torque<br>Wheels<br>Steering | | x | |
| Pressure<br>Compartments<br>Wheel housings | | x | |
| Angles<br>Steering<br>Sensors<br>Antennas<br>Solar Array | | x | |
| Positions<br>RI Pellet<br>Clutches<br>Brakes | | x | |
| Vibration, Shock | | x | |

Table 6-2
BASIC PARAMETERS FOR TERRAIN STATES

| Quantity to be Determined | Basic Parameters | Direct Measurement | Indirect Measurement | |
|---|---|---|---|---|
| Terrain Slope<br>Relative to local vertical & vehicle heading | Roll and pitch operating range<br>Integration requirements<br>Measurement accuracy<br>Sampling rate | x | x | |
| Terrain Slope<br>Relative to vehicle | Surface height above horizontal as functions of distance & azimuth<br>Azimuth<br>Range of distances from vehicle<br>Measurement accuracy<br>Sampling rate | x | x | * |
| Protruding Features<br>Relative to vehicle | Height above surface<br>Width<br>Azimuth<br>Range of distances from vehicle<br>Geometry (i.e., slope of face, sharpness of corners)<br>Spacing between features<br>Measurement accuracy<br>Sampling rate | x | x | * |
| Concave Features<br>Relative to vehicle | Distance below surface<br>Width<br>Azimuth<br>Range of distances from vehicle<br>Geometry<br>Spacing between features<br>Accuracy requirements<br>Sampling rate | x | x | * |
| Soil Characteristics | Bearing strength<br>Stability<br>Azimuth<br>Range of distances<br>Measurement accuracy<br>Sampling rate | x | x | * |

* Subject to limits due to obscuration.

Table 6-3
BASIC PARAMETERS FOR ENVIRONMENTAL STATES

| Quantity to be Determined | Basic Parameters | Direct Measurement | Indirect Measurement |
|---|---|---|---|
| Wind | Direction<br>Velocity<br>Pressure<br>Measurement accuracy<br>Sampling rate | x | |
| Blowing Dust | Quantity<br>Measurement accuracy<br>Sampling rate | x | x |
| Visibility | | x | x |
| Cloud Coverage | | x | x |
| Light | Intensity<br>Direction<br>Measurement accuracy<br>Sampling rate | x | x |
| Temperature | Operating range<br>Measurement accuracy<br>Sampling rate | x | |
| Magnetic Field Int. | | x | |
| Radiation Flux | | x | |
| Meteoritic Flux | | x | |

Table 6-4
BASIC NAVIGATION PARAMETERS

| Quantity to be Determined | Basic Parameters | Direct Measurement | Indirect Measurement |
|---|---|---|---|
| Vehicle Position<br>Relative to a lunar or planetary coordinate system | Vehicle position<br>Measurement accuracy<br>Sampling rate | x | x |
| Vehicle Position<br>Relative to landmarks and/or previous vehicle positions | Distance traveled<br>RV heading history<br>Initial position<br>Distance and bearing to terrain features<br>Measurement accuracy<br>Sampling rate | x | x |
| Vehicle Heading<br>Relative to lunar or planetary coordinate system | Vehicle heading<br>Measurement accuracy<br>Sampling rate | x | x |
| Vehicle Heading<br>Relative to surface features | Azimuth to surface features<br>Measurement accuracy<br>Sampling rate | x | x |
| Distance Traveled | Distance traveled<br>Measurement accuracy<br>Sampling rate | x | x |

In Section 5, configurations were discussed for each of the six mission modes. In each case the system configuration consists of an assembly of more or less "standard" subsystems — mobility, telecommunication, sensory, data processing, displays, and operational personnel. The configurations differ mainly in the routing or flow of information and in the relative emphasis or importance of the role assumed by each of the elements. As one proceeds from the fly-by-wire to the fully automatic mode, increasing emphasis is placed upon space-based appraisal of sensed data and less emphasis is therefore placed on telecommunications and ground-based displays and personnel.

When one considers the ways of implementing each of the subsystems it soon becomes apparent that the most difficult problems arise in two areas: (1) Sensing and (2) Appraising. That is, the major difficulties are associated with gathering the information needed for valid and effective control decisions and then assimilating the data so acquired to permit making the appropriate decisions.

These are not independent problems by any means. The type, quantity, and quality of information needed are intimately related to the means applied to appraising it. If the appraisal is to be conducted on earth one can consider the use of human intelligence and its particular abilities of subjective interpretation and pattern detection and/or recognition. However, this requires transmission of the information across space at restricted bandwidths and significant time lags. If the appraisal is space-based the human cannot be used and the sensory elements must then be chosen to be compatible with realizable data processing mechanizations.

A sensor subsystem is here defined as one which not only senses inputs but also reports the information in a form suitable for appraisal and decision-making by man or machine. The reason for this inclusive definition is that while a particular system might include data processing, displays, and human interpretation, another system might directly provide the required information for decision making.

For example, using stereo imagery it is necessary to:

1. Detect and identify an obstacle
2. Measure the obstacle.

This information may then be used to make an appraisal of the significance of the measurement to the problems of motion control.

A device which directly measures range, azimuth, and elevation of surface points does not require the pattern recognition function to be performed in order to prepare the sensed information for appraisal. It is inherently contained in the output of the device. However, this may be at the cost of ignoring subtle factors.

There are a number of candidate sensor and display subsystem configurations for exploration of the moon and planets using a remotely controlled vehicle. Figure 6-1(a) is a functional block diagram of a typical simple system. Information concerning vehicle/terrain relationships is transmitted to earth in the form of video information, sun compass readings, clinometer readings, odometer readings and range and bearing from the landing vehicle. Engineering data such as vehicle component temperatures, electrical conditions, camera orientation, steering position and power reserve are sensed and transmitted to earth. Additional video and miscellaneous measurements may be made for scientific purposes. In addition, feelers, tilt and roll switches, or similar sensors may be used to stop the vehicle without earth command if the vehicle encounters a hazardous condition. On earth the images and other data are analyzed and appropriate commands transmitted to the vehicle.

Figure 6-1(b) is essentially the same, except that data compression is provided to limit the amount of data transmitted to the earth by various techniques to be discussed later.

Figure 6-1(c) shows the addition of a computer which, in addition to data compression, can perform analysis of images and/or other data to control the vehicle directly. This approach may be carried to rather high levels of sophistication, as exemplified by work now being done at MIT.[12] For example, among other approaches, MIT proposes the reduction of pictures to line drawings which can be transmitted to earth users at a higher compression ratio than unprocessed video.

Figure 6-1 configurations assume that the roving vehicle is operated independent of the lander. However, the lander might include an imaging system and/or range and bearing equipment for observation of the roving vehicle. From an information standpoint an advantage of navigation control from the lander is that only the vehicle position and orientation are changing in the field of view. Positional accuracy would be better than with dead reckoning from the vehicle. Disadvantages are obscuration effects and curvature of the terrain for great distances. This might be a useful approach during the earliest stages of a mission to help in the development of technique.

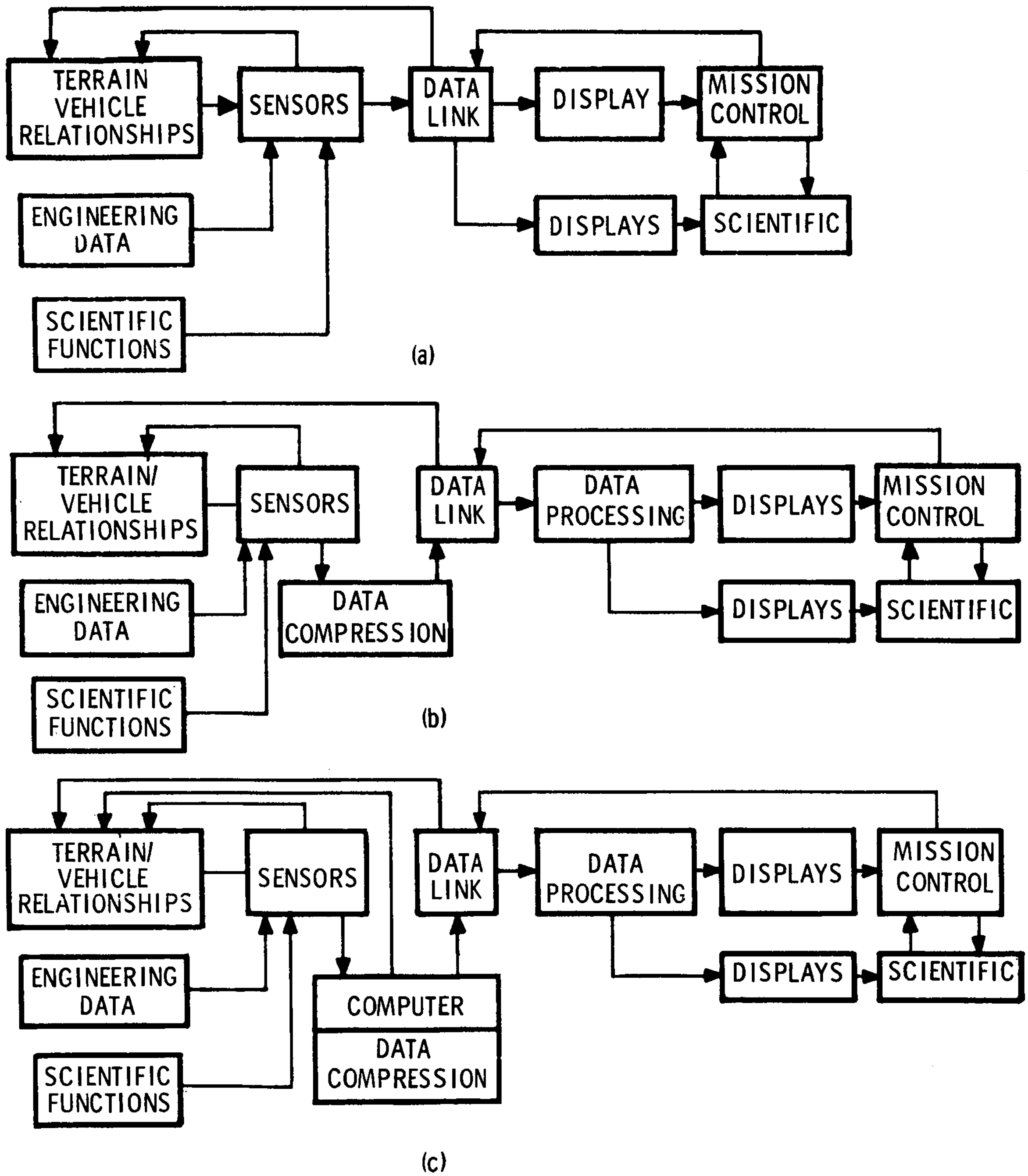



Figure 6-1 Sensor Subsystem Configurations

### 6.1.3 Geometrical Surface Assessment

For purposes of remote vehicle control it is necessary to choose a path which leads toward the goal and which does not exceed vehicle mobility capability. A priori information about the terrain will generally be insufficient to make all judgments ahead of time. Furthermore, uncertainties in the drive and steering controls and navigation errors would make such a predetermined path infeasible even if the data were available. Therefore, it seems quite certain that the vehicle will be required to carry sensors to assess local terrain conditions.

Basically, techniques and associated sensors for surface assessment which will permit collection of the required information fall into three classes:

- Imaging Systems
- Ranging Systems
- Tactile Devices

In general, imaging systems require a high order of intelligence for interpretation of oblique views of the surface. This is reflected in difficulties associated with making the appraisal and decision processes automatic, and it therefore generally requires the transmission of data to earth for assimilation. Ranging systems can be mechanized in relatively simple fashion to perform the functions required for control. On the other hand the quantity of information produced (both useful and not useful) is much greater from existing imaging systems than from existing ranging systems. This need not be the case and solutions are suggested.

In addition to their relative adaptability to automation, other functional considerations in choosing techniques and sensors are

- Maximum range and ranging accuracy
- Demands on the data link to earth to give the required resolution, geometrical surface information, and frame rate
- Commonality of equipment for performing different functions.

a. Obscuration. From a particular vantage point significant portions of the terrain may very likely be obscured from view of the sensors. Terrain obscuration is a function of

- Range and height or depth of surface features relative to a reference plane
- Height of vantage point relative to the reference plane.

For actual surfaces, obscuration depends on the statistics of the terrain geometry. For purposes of initial analysis it is sufficient to establish a simplified mathematical model. Figure 6-2 shows the geometry of the area obscured by a cone and a rectangle.

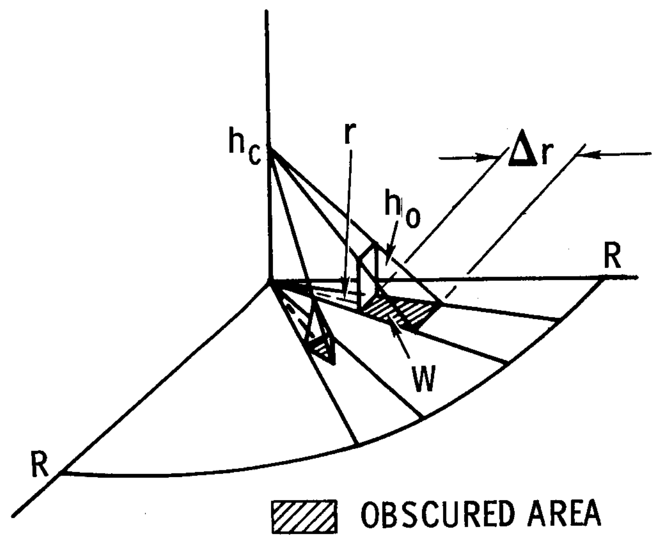



Figure 6-2 Model of Terrain Geometry

From Figure 6-2 it can be shown that

$$\Delta r = \frac{r}{h_c/h_o - 1} \tag{6-1}$$

where $h_o$ = object height above a reference plane

$h_c$ = height of vantage point above the reference plane

$r$ = distance to obstacle

$\Delta r$ = length of obscured area

$R$ = Maximum distance in the quadrant of interest.

Figure 6-3 shows plots of $\Delta r$ versus $r$ for ratios of 2, 4 and 8 for camera height to object height.

Thus, for example, with a camera 2 meters high a one meter object at a distance of 200 meters will obscure the ground out to 400 meters. Increasing camera height to 4 meters will reduce the ground obscuration length to 66 meters. If the object were a continuous ridge, 75% of the area out to 400 meters would be obscured in the first case and 19% in the second case. While the tops of equal-height objects would be visible in the obscured area, their bottoms would be obscured preventing height determination.

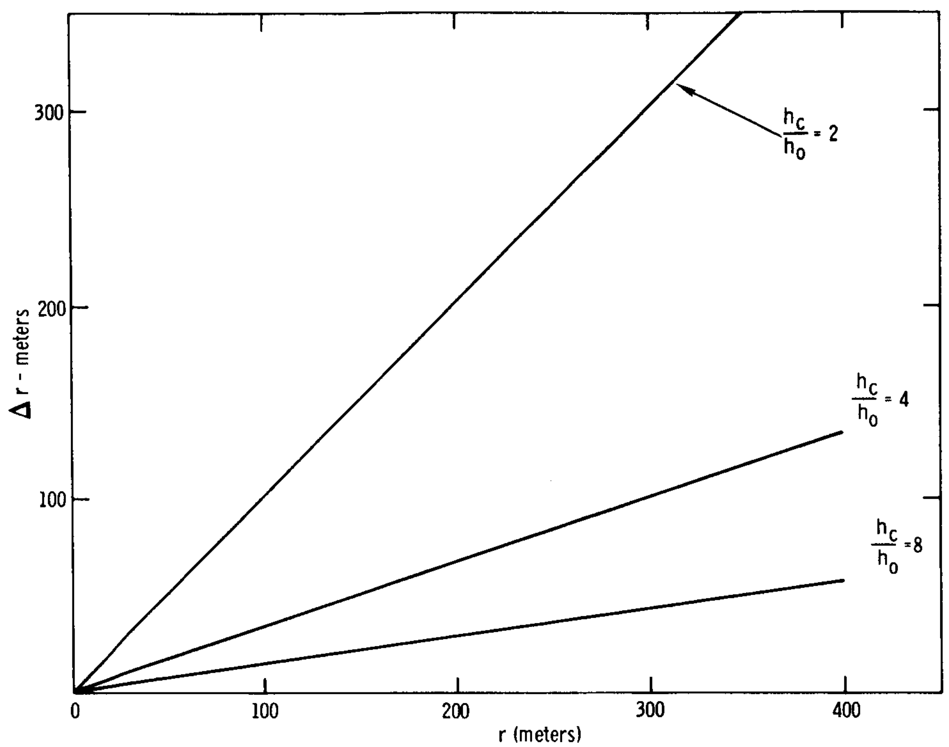



Figure 6-3 Obscuration vs Range

In considering the possibility of long (say 200 to 400 meter) steps it can be seen from Figure 6-3 that a ridge 0.25 meter high at a distance of 100 meters could completely conceal a crevice 6.66 meters wide assuming a 4-meter camera height. Therefore hazard detection may not be possible at distances of several vehicle lengths.

Likewise the near edge of a depression can obscure all but a portion of the far wall, as shown in Figure 6-4.

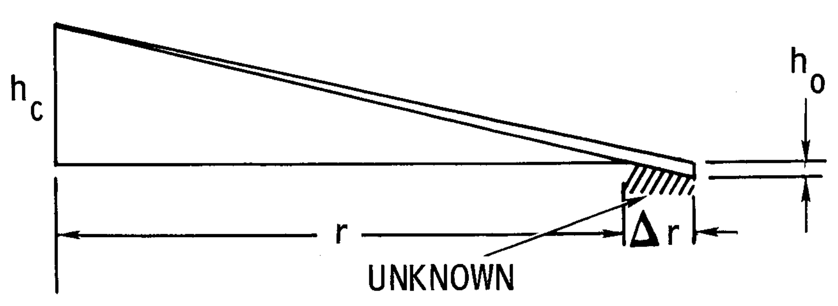



Figure 6-4 Obscuration of Depressions

From Figure 6-4

$$h_o = \frac{\Delta r \cdot hc}{r}$$

The question arises as to how close the vehicle must be to a wide crevice to determine if the crevice depth is within the step-climbing capability of the vehicle. Assume $h_o$ is 0.5 meter, $h_c$ = 4 meters and $\Delta r$ = 2 meters. Then

$$r = \frac{\Delta r \; h_c}{h_o} = 16 \text{ meters.}$$

Again it is evident that hazard detection cannot be accomplished at distances of tens of meters.

An analytical and computer analysis of obscuration effects was made under the SLRV Phase I Study.[13]

Using the mathematical model shown in Figure 6-2 the curves shown in Figures 6-5 and 6-6 were derived analytically and confirmed by a computer Monte Carlo statistical technique where

n = Size distribution exponent

N = Number of obstructions in a 200 x 200 meter square area

h = Observer height in meters

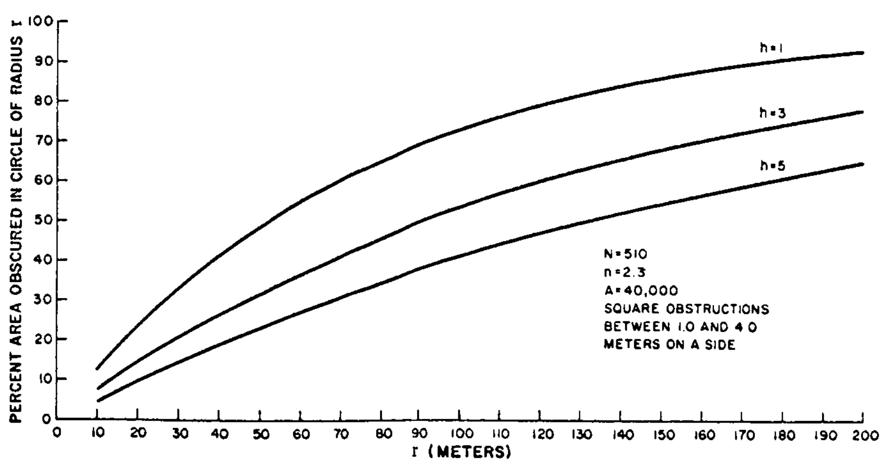



Figure 6-5 Obscuration Effects, N=510

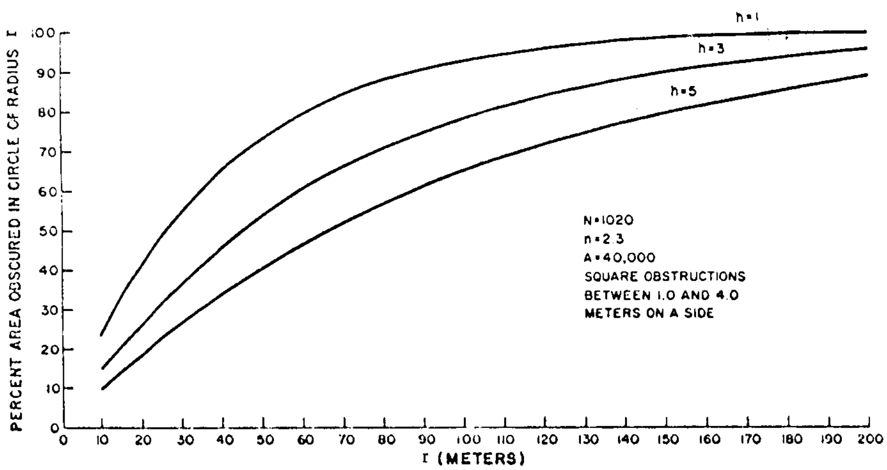



Figure 6-6 Obscuration Effects, N=1020

b. Monoscopic Images. A single image contains a record of the azimuth and elevation of surface points with respect to the camera lens axis. No information is available concerning the absolute range of points except for focus changes with distance. While focus might provide some useful information, at best it would provide distance information with range accuracies of 5 feet at a 20-foot range and 35 feet at a 50-foot range.

A human viewing a single image can often make a judgment as to the negotiability of a proposed path using some of the following clues:

- Relative sizes of known objects or texture
- Comparison with previous experience
- Perspective
- Position of one object in front of another
- Variations in sharpness as a function of range
- Shadows
- Color and shading
- Texture compression.

In many cases these clues are not sufficiently well defined for the interpreter to make a valid judgment. Except for very special subjects, machines are not available to make such judgments at all. From the above, it can reasonably be concluded that, where monoscopic images are used for terrain assessment, they must be transmitted to earth for human interpretation.

c. Stereo Images. Each member of a stereo pair contains a record of the azimuth and elevation of each surface point with respect to its respective camera lens axis. A human interpreter can usually detect similar patterns representing the same feature in the two pictures and fuse them visually to determine qualitatively, the three-dimensional nature of the subject. If the length of the stereo baseline and the orientation of the lens axes are known, the size and distance of objects can be measured using visual aids or photogrammetric techniques.

No automatic machines have yet been built to do this reliably in the case of oblique views containing abrupt discontinuities and subtle patterns. Development work at MIT and at Stanford Research Institute is aimed toward a computerized solution to this problem. It remains to be seen whether this can be accomplished within the practical constraints of lunar and planetary systems, and if so how such a mechanization compares with the direct ranging methods discussed in the following section.

It seems likely that stereo imaging, where used, will not be primarily directed at measurement of sizes or distances, but will merely provide a human viewer with a three-dimensional concept of the milieu in which the vehicle is operating. To provide measurement capability in addition would require considerably greater sensor precision, elaborate equipment on earth, and time-consuming operations to correct for sensor deficiencies.

The advantage of stereo in this type of application is that a human operator can make rapid judgments about potential hazards without much cost in equipment. In a fly-by-wire mode (which is the only mode in which stereo imaging would be of routine use), the operator might be aided by a simple, direct ranging device of the type described below. In a lunar situation he could simply direct the ranging device at objects of interest detected in the stereo images. This would probably not be feasible in Martian missions because of the long communication delays. Then, for Martian fly-by-wire operation an automatic means is required for orienting a ranging device.

d. Ranging Systems. The advantage of a system which senses distance, azimuth and elevation to surface points has been identified as primarily the capability for readily utilizing the outputs in automatic appraisal modes. There are further advantages and disadvantages compared to an imaging system. Advantages are:

- Measurement of surface geometry is independent of lighting angle. For front lighting where features in an image are lacking in contrast, a ranging system would provide better information.
- If a fly-by-wire mode is used, information bits transmitted would be fewer than for, say, transmission of a stereo pair, because the resolution and geometrical accuracy requirements for stereo measurements would no longer be necessary.

Disadvantages are:

- Natural shadows will not be available as clues to interpretation. For automatic modes this distinction is not of immediate importance because automatic interpretation of shadows in an image is unlikely in the next few years.
- In the near future it is unlikely that subtle features often detectable by a human in an image can be adequately sensed by a ranging system. These include such things as an unstable slope, small features that might wedge a wheel, etc. However, for automatic appraisal it is also unlikely that a machine will soon be developed to detect these subtle features in images.

e. Direct Image Evaluation. A class of techniques such as detection of motion parallax by spatial filtering would permit deriving terrain assessment information directly from optical images. Two advantages of such an approach over, say, stereo imaging are

- Information is derived from a high-quality image not degraded by scanning, transmission degradation etc.
- Desired quantities are derived directly without the necessity for pattern recognition and associated human-type skills.

While similar devices have been used in various tracking and detection systems, considerable development would be required to determine feasibility for RV control. This method is discussed further below.

f. Choice of Sensor Subsystem Configurations. From the foregoing discussion sensor subsystems for terrain assessment can be classified as in Table 6-5. Use of a system for the fly-by-wire mode is predicated upon the availability of an adequate data link capacity. Use of ranging and direct image evaluation will depend upon future successful development.

Table 6-5
CLASSIFICATION OF TERRAIN SENSORS

| | Fly-by-wire | Semi-Automatic | Fully-Automatic |
|---|---|---|---|
| Monoscopic Images | Usually Adequate | Not useful except for monitoring | Not useful |
| Stereo Images | Excellent | For monitoring Routine Control* | Routine Control* |
| Ranging Systems | Usually Adequate* | Good* | Good* |
| Direct Image Evaluation | Usually Adequate* | Excellent* | Excellent* |

* Depends on future development.

### 6.1.4 Sensor Hardware, Techniques and State-of-the-Art

Each quantity which may have to be determined for purposes of RV control is listed in the first column of Tables 6-6 through 6-9. For each quantity, alternative techniques and associated sensors are shown.

The reasons for classifying "quantities to be determined" as shown are discussed in the following sections. In particular one is concerned with whether or not a quantity can be measured directly or whether it must be computed from several sensed quantities. Also, if possible, it is desirable to choose techniques and sensors which do not require such operations as pattern recognition.

a. Image Sensors. Table 6-10 is a tabulation of existing and proposed image sensors and important parameters related to system design.

The choice of an image sensor is dependent on performance requirements and system implications such as weight, volume, power required and reliability.

Performance parameters relating to RVMC are set by requirements for safe mobility and for navigation. Performance parameters relating to scientific functions are set by needs for accurate information concerning surface features.

Table 6-6
TECHNIQUES FOR DETERMINING RV STATES

| Quantity to be Determined | Technique | Quantities Sensed | Possible Sensor | Required Data | Computation and/or Interpretation |
|---|---|---|---|---|---|
| RV Attitude<br>With respect to local vertical | Direct measurement | Local vertical | Liquid pendulum, Pendulous Accelerometer, Clinometer | None | None |
| RV Attitude<br>With respect to horizontal reference | Observe terrain | Horizon | Imaging system, Horizon sensor | Sensor orientation relative to RV | Coordinate transformation |
| | Inertial | Vehicle attitude relative to stable platform | Angle readout transducers | None | None |
| RV Attitude<br>With respect to astronomical bodies | Direct observation | Azimuth & elevation of sun, earth or stars | Imaging system | Star charts, orientation of sensor relative to vehicle | Correlation, coordinate transformation |
| | | | Sun, star or earth sensor | Orientation of sensor relative to vehicle | None |
| Temperature<br>Motors<br>Compartments<br>Sensors<br>Battery<br>RTG | Direct measurement | - | Thermocouple<br>Thermistor<br>Other | None | None |
| Electrical<br>Power<br>Current<br>Voltage | Direct measurement | Power | Microcoulombmeter<br>Wattmeter | None | None |
| | | Voltage & current | Voltmeter<br>Ammeter | None | None |
| Force & Torque<br>Wheels<br>Steering | Direct measurement | Force | Strain gages<br>Motor currents | None | None |
| Pressure<br>Compartments<br>Wheel housings | Direct measurement | Pressure | Pressure transducers | None | None |
| Angles<br>Steering<br>Sensors<br>Antennas<br>Solar Array | Direct measurement | Angle | Transducers | None | None |
| | | | Imaging system | Sensor orientation | Coordinate transformation |
| Positions<br>RI Pellet<br>Clutches<br>Brakes | Direct measurement | - | Limit switches<br>Linear potentiometer | | |
| Vibration, Shock | Direct measurement | - | Accelerometer | None | None |

## Table 6-7
## TECHNIQUES FOR DETERMINING TERRAIN STATES

| Quantity to be Determined | Technique | Quantities Sensed | Possible Sensor | Required Data | Computation and/or Interpretation |
|---|---|---|---|---|---|
| Terrain Slope<br>Relative to local vertical & vehicle heading | Direct measurement | Attitude of axles with local vertical | See Vehicle Attitude | None | Adjustment for twisting of vehicle |
| Terrain Slope<br>Relative to vehicle | Direct contact | Surface height relative to vehicle as functions of range and azimuth | Mechanical feelers | None | Compute slope from sample points |
| | Judgement from monoscopic image | Azimuth and elevation of surface points relative to camera axis | Vidicon Camera<br>Secon Camera<br>Facsimile Camera<br>Photographic Camera<br>Solid State Camera | See text | See text |
| | Judgement from stereo images (measurement where necessary) | Azimuth & elevation of surface points relative to each of two camera axes | Vidicon Camera<br>Secon Camera<br>Facsimile Camera<br>Photographic Camera<br>Solid State Camera | Length of baseline<br>Attitude of optical axes | Stereo viewing<br>Photogrammetric measurements |
| | Ranging to surface points | Azimuth, elevation and range to surface points | Laser Range Finder<br>Optical Pulse Range Finder<br>Split Field Range Finder<br>Radar Ranging<br>Sonic Ranging | None | Direct measure of roughness |
| | Motion parallax and spatial filtering | Relative rates of movement of points in image of surface | See text | None | Safe path selected by the device |
| Protruding Features<br>Relative to vehicle | Direct contact | Presence of protruding feature | Mechanical feelers<br>Bumper switches | None | |
| | Judgement from monoscopic image | Same as slope | Same as slope | Same as slope | Same as slope |
| | Judgement from stereo images (measurement where necessary) | | | | |
| | Ranging to surface points | | | | |
| | Motion parallax and spatial filtering | | | | |
| Concave Features<br>Relative to vehicle | Direct contact | Presence of concave feature | Mechanical feelers | None | Compute slope from sample points |
| | Judgement from monoscopic image | Same as slope | Same as slope | Same as slope | Same as slope |
| | Judgement from stereo images (measurement where necessary) | | | | |
| | Ranging to surface points | | | | |
| | Motion parallax and spatial filtering | | | | |
| Soil Characteristics | Surface contact | Bearing strength<br>Cohesiveness | Bevameter<br>Soil Mechanics Inst. | Previous calibration | Can be direct readout |
| | Judgement from monoscopic image | General appearance | Vidicon Camera<br>Secon Camera<br>Facsimile Camera<br>Photographic Camera<br>Solid State Camera | Previous experience | Photointerpretation |
| | Judgement from stereo image (measurements where required) | General appearance and three-dimensional characteristics | Same | Previous experience | Photointerpretation |
| | Seismic | Sound reflections | Microphone-thumper | - | - |

Table 6-8
TECHNIQUES FOR DETERMINING ENVIRONMENTAL STATES

| Quantity to be Determined | Techniques | Quantities Sensed | Possible Sensor | Required Data | Computation and/or Interpretation |
|---|---|---|---|---|---|
| **Wind Direction** | Direct | Angle | Wind vane, pressure transducer array | None | None |
| **Wind Velocity** | From pressure | Pressure | - | Atmospheric density | Calibration |
| **Wind Pressure** | Direct | - | Pressure transducer | None | None |
| **Blowing Dust** | Indirect | Pressure | Pressure transducer | - | Wind or dust |
| | Direct | Contact frequency | Particle detector | None | - |
| **Visibility** | Observation | Obscuration | Imaging system | Prior images | Judgement |
| **Cloud Coverage** | Observation | Obscuration | Imaging system | Prior images | Judgement |
| **Light Intensity** | Direct | - | Imaging system, Light sensor | Sensor calibration | Photometric |
| **Temperature** | Direct | - | Thermocouple<br>Thermistor<br>Other | None | None |
| **Magnetic Field Int.** | Direct | - | | None | None |
| **Radiation Flux** | Direct | - | | None | None |
| **Meteoritic Flux** | Direct | - | | None | None |

## Table 6-9
## TECHNIQUES FOR DETERMINING NAVIGATION PARAMETERS

| Quantity to be Determined | Technique | Quantities Sensed | Possible Sensors | Required Data | Computation and/or Interpretation |
|---|---|---|---|---|---|
| Vehicle Position<br>Relative to a lunar or planetary co-ordinate system | DSIF tracking from earth | In-flight track, Doppler shift | - | - | |
| | Optical tracking from earth | Position of laser or sun reflector on surface | Telescope | Reference maps or photos | Correlation |
| | Observe from orbiting module | Position of vehicle on surface | Telescope<br>Camera | Location of visual field relative to coordinate system | |
| | Celestial fix from RV | Location of star or stars<br>Location of sun | Television<br>Star tracker<br>Sun sensor | Reference star field or star tables | Correlation |
| Vehicle Position<br>Relative to land-marks and/or previous vehicle positions | Dead reckoning | Distance traveled (history) | See distance traveled below | None | Vector summation |
| | | RV Heading (history) | See vehicle heading below | None | |
| | Pure inertial | Acceleration components of velocity vector | Inertial system | Initial position | Integration and vector summation |
| | Correlation | Terrain characteristics | Imaging system | Map or photo | Visual correlation |
| | | Slope | Clinometers | Contour map | Cross correlation |
| | Observe from orbiting vehicle | RV relative to terrain features | Telescope, camera | Previous terrain data | Visual correlation |
| | Measurement from surface features | Distance & bearing to one feature | Laser range finder<br>Optical range finder<br>Stereo imaging<br>Radio range & bearing | None | None |
| | | Bearing to one feature from two known points | Theodolite<br>Imaging system<br>Radio direction finder | Distance apart of points | Trigonometric calculation |
| Vehicle Heading<br>Relative to lunar or planetary co-ordinate system | Celestial | Sun position<br>Star positions | Fixed sun compass<br>Stabilized sun compass<br>Imaging system | Roll, pitch, ephemeris | Coordinate transf.<br>Trig. calculation |
| | Inertial heading | Azimuth deviations from initial azimuth | Stable platform & directional gyro | Initial heading | None |
| | Gyro compass | Rotation rate of body | Stable platform | None | None |
| | Magnetic field | - | Magnetic compass | Declination | Subtraction of angles |
| | Observe from orbiting module | RV heading relative to visual field | Telescope, camera | Relation of visual field to coordinate system | Subtraction of angles |
| Vehicle Heading<br>Relative to surface features | Direction to surface features | - | Theodolite<br>Imaging system<br>Radio direction finder | Angle of sensor with vehicle | Identification of surface feature |
| Distance Traveled | Wheel rotation | Wheel rotation | Odometer | Distance/revolution | Integration |
| | | Wheel rotation | Wheel pulse transducer | Distance/revolution | Addition |
| | Speed x time | Wheel speed | Speedometer | Movement time | Multiplication or Integration |
| | Inertial | See vehicle position | - | - | From positions |
| | Measurement from surface features | See vehicle position | - | - | From positions |

# Table 6-10
# IMAGE SENSORS

| | SYSTEM | Camera | Active Lines | Hor. Resolution | Vert. Resolution | Exposure (Seconds) | Frame Readout Time (Seconds) | Frame Time (Seconds) | Number of Picture Elem. | Grey Levels | Total Bits Per Frame | Face Plate Dynamic Range (Foot Candles/Second) | Scene Dynamic Range (Foot Lamberts) | Residual Image | Geometrical Linearity | Photometric Accuracy | Size Stability | Centering Stability | Fiducial Marks | Color Filters | Aperture | Field Angle | Power (Watts) | Weight (Pounds) | Vol. (Cu. In.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOON | Ranger 3, 4, 5 | 1" Vidicon | 200 | 200 | 150 | .020 | 10 | | *$4 \times 10^4$ | *64 | *$2.4 \times 10^5$ | .3-.01 | <2700 | <10% | 1% | ±20% | | | Yes | No | | | | | |
| MOON | Ranger 6, 7, 8, 9 (F) | " | 1152 | 700 | 700 | .005 | 2.56 | 5.12 | *$1.3 \times 10^6$ | *64 | *$8.4 \times 10^6$ | .68-.004 | <2700 | <17% | 1% | | | | Yes | No | f/1 f/2 | 25° 8.4° | 18.5 | 15 | |
| MOON | " (P) | " | 300 | 200 | 200 | .002 | 0.2 | 0.84 | *$9 \times 10^4$ | *64 | *$5.4 \times 10^5$ | .27-.003 | <2700 | <10% | 1% | | | | Yes | No | f/1 f/2 | 6.3° 2.1° | | | |
| MOON | Surveyor 1 (600 Line) | " | 600 | 600 | 420 | .150 | 1.0 | 3.6 | *$3.6 \times 10^5$ | *64 | *$2.16 \times 10^6$ | .001-.6 | .008-2600 | 6% | 1% | | <6.5% | <1.5% | 5 x 5 Dots | Red/ Green/ Blue | f/4 f/22 | 6.43° 25.3° | | 16.1 | |
| MOON | " (200 Line) | " | 200 | 200 | 140 | .150 | 20 | 60.8 | *$4 \times 10^4$ | *64 | *$2.4 \times 10^5$ | .001-.6 | .008-260 | 6% | 1% | | <6.5% | <1.5% | 5 x 5 Dots | Red/ Green/ Blue | f/4 f/22 | 6.43° 25.3° | | 16.1 | |
| MOON | SLRV Phase I AC-DRL (RCA) | " | 716 | 500 | 500 | — | 0.9 | 1.0 | *$5.1 \times 10^5$ | *64 | *$3.08 \times 10^6$ | .015-34 | 22 to 2200 | 5% | 5% | — | — | — | 5 x 5 Dots | No | f/4 | 45° | 11.6 | 5.75 | |
| MOON | SLRV Proposal AC-DRL (RCA) | " | 716 | 500 | 500 | — | 1.58 | 3.72 | *$5.1 \times 10^5$ | *64 | *$3.08 \times 10^6$ | .015-34 | 22 to 2200 | 5% | 1% | — | — | — | 5 x 5 Dots | No | f/3.5 | 42° | 4.8 | 4.1 | 47 |
| MOON | Orbiter 1, 2, 3 | 70mm film Photoscan | 18,942 /strip | — | — | 1/25, 1/50 1/100 | 20 Min | — | *$9.6 \times 10^8$ | *64 | *$5.75 \times 10^9$ | — | — | — | | | | | Yes | No | f/5.6 | | | 145 Incl. Proc | 26x22 x32 |
| MOON | Apollo (Surface) | 1" Secon | 320 | | | | 0.10 | 0.10 | *$1 \times 10^5$ | *64 | *$6.1 \times 10^5$ | | .007-12,600 | | 2% | | | | | | | 70° | 6.5 | 7.25 | 160 |
| MOON | " " | 1" Secon | 1280 | | 500 | | 0.625 | 0.625 | *$1.6 \times 10^6$ | *64 | *$9.8 \times 10^6$ | | " | | 2% | | | | | | | 70° | 6.5 | 7.25 | 160 |
| MOON | Apollo (Command) | 1" Vidicon | 320 | 220 | 220 | — | 0.1 | 0.1 | *$1 \times 10^5$ | *64 | *$6.1 \times 10^5$ | 0.1 -30 | | | | | | | | | f/1.9 f/2.5 | 80° | 5.8 | 4.5 | 84 |
| MOON | Facsimile (Aeronutronics) | Scanner | 500 | 0.10 -0.01° | 0.1° | | 60 for 360° | | | *64 | | | 25-2200 | | 0.2% | 1% | | | | | f/7 | 50° x 360° | <10 | 10 | 49 |
| MARS | Mariner IV | Vidicon | 200 x 200 | 140 | 140 | 0.20 | 24 | 48 | $4 \times 10^4$ | 64 | $2.5 \times 10^5$ | | | | | | | | Yes | Yes | f/8 | 32 Min of arc | | Head 3.5 | |
| MARS | Voyager 1973 (Entry) | " | 200 x 200 | 140 | 140 | | | | | 64 | $2.5 \times 10^5$ | | | | | | | | | | | | 20 | 14 | 700 |
| MARS | Voyager 1973 (Capsule) | | | | | | | | | | | | | | | | | | | | | | 25 | 15 | 1500 |
| MARS | Surveyor Study (Hughes) | 1" Vidicon | 600 200 | 700 200 | 700 200 | | | | $3.6 \times 10^5$ $4 \times 10^4$ | 64 64 | $2.16 \times 10^6$ $2.4 \times 10^5$ | | To 5000 | 6% 6% | 1% 1% | | | | 5 x 5 | 3 Color | | | | 16.1 | |
| MARS | Orbiter Study (Boeing) | 1" Vidicon | 200x200 400x400 | 140 280 | 140 280 | 0.20 0.20 | — 26 | — 52 | $4 \times 10^4$ $1.6 \times 10^5$ | 64 64 | $2.4 \times 10^5$ $9.6 \times 10^5$ | | | | | | | | | | | | 10.5 | 13.5 | |
| MARS | Orbiter Study (JPL) | 70 x 25mm Film | 2100 x 750 | | | .170 | — | — | $1.6 \times 10^6$ | 64 | $10^7$ | — | 280 | | | | | | | | f/4.5 | 24° | | | |

* Digital Equivalent

As previously discussed, the maximum distance for terrain assessment for vehicle control will usually be limited by obscuration effects rather than sensor capability. For navigation and scientific functions this will not be the case and the highest possible resolution and geometrical fidelity can be utilized. High image quality is achieved at the cost of increased frame time, which is undesirable for vehicle control.

Therefore, the choice of an image sensor will depend on scientific and navigational requirements and the capability of operating in a degraded mode for vehicle control purposes. An image sensor is only one link in the chain for producing an image output useful to man and/or machine. Thus the choice of an image sensor also depends on all other components of the sensor subsystem, including the final display.

b. Non-Imaging Sensors for Terrain Assessment.

(1) Direct Ranging Devices — A laser, noncoherent optical, radar or sonic-type ranging device using time of return for a pulse provides direct readings of range from the vehicle to a reflecting surface point as a function of azimuth and elevation. Pulse rate must be low enough, as a function of maximum range, to prevent ambiguous returns. Only laser ranging or noncoherent optical pulse ranging would appear to offer adequate resolution and signal-to-noise ratio for vehicle control purposes.

One or several such devices, with fixed axes, would be adequate to detect a large obstacle in front of the vehicle. Many such devices would be required to provide sufficient coverage at close enough spacing for accurate surface assessment. This does not appear practical but if one rangefinder were used in a scanning mode, surface coverage could be adequate.

Published information[14, 15] indicates that most commercially available laser rangefinders of this class are for high-power (kW), long-range (miles) applications, It is not yet evident whether laser equipment suitable for an RV can be or will be developed.

Optical pulse-ranging experiments,[16] using a noncoherent source, have demonstrated accuracies within a few cm at ranges from 10 to 100 meters. Short-burst repetition rates of about $10^4$ pps are possible. Equipment reportedly would be simple and light weight.

(2) Active Triangulation Devices — A number of optical systems have been built which sense objects at fixed ranges as established by the point of intersection of converging transmitter and detector beams. Transmitters have included lasers[14] and GaAs[17, 18] diode emitters. For discrimination against ambient light, the output of the diode emitters is usually pulsed at a frequency such as 10 KHz.

In order to scan a volume it is necessary to vary convergence of the two beams as well as azimuth and elevation. This, plus the fact that such triangulation devices are inherently accurate only at short ranges, makes them most useful as fixed range sensors for nearby obstacles.

Active optical triangulation methods are based on detecting an object which lies in the volume formed by the intersection of a transmitted beam of light with the field of view of a detector. A typical configuration is shown in Figure 6-7.[14]

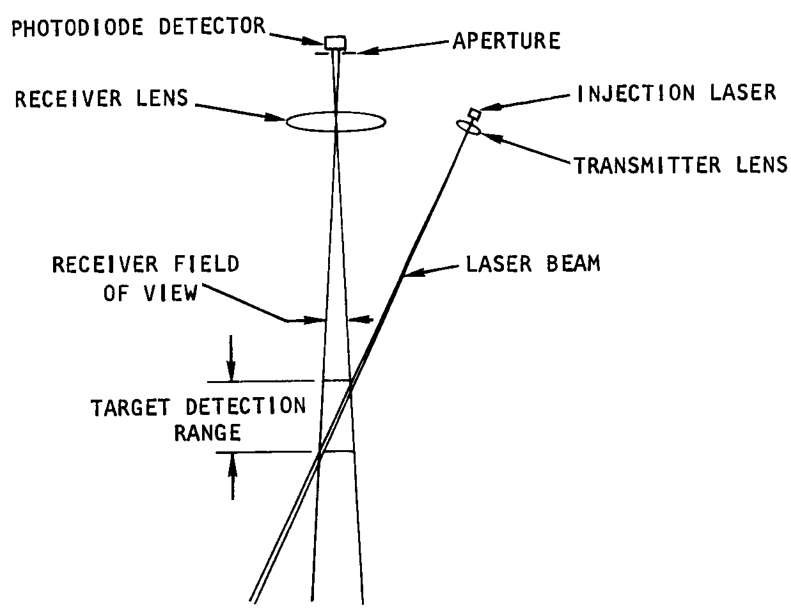



Figure 6-7 Laser Ranging Configuration

In such a system one is interested in performance with regard to range resolution, azimuth and elevation resolution and accuracy, maximum range and ability to discriminate between objects in the beam intersection and other sources of light lying in the detector beam.

These performance parameters are controlled by system geometry and system signal to noise ratios as follows:

Parameters affecting range resolution

Beam width of transmitter

Field of view of the detector

Baseline (Distance between transmitter and detector)

Distance to point of convergence

Parameters affecting azimuth and elevation resolution

Beam width of transmitter

Field of view of the detector

Parameters affecting maximum range

Transmitted energy and beam width

Energy reflected from object within detector field

Detector sensitivity and aperture diameter

Level of background, and receiver noise

Spectral and frequency selectivity of the system

Parameters affecting target discrimination

Spectral and frequency selectivity of the system

Level of background and receiver noise

System Geometry

System geometry is shown in Figure 6-8 where:

$L$ = Distance between transmitter and receiver along the baseline

$\theta_1$ = Angle between baseline and inner edge of detector field of view

$\Delta\theta_1$ = Detector field of view

$\theta_2$ = Angle between baseline and inner edge of transmitter beam

$\Delta\theta_2$ = Transmitter beam width

$D$ = Distance from baseline to nearest point of intersection of transmitter beam and detector field of view

$D'$ = Distance from baseline to farthest point of intersection of transmitter beam and detector field of view

$\Delta D$ = Length of interception, perpendicular to the baseline.

It will be assumed that $\theta_1$ is always $90^o$. From Figure 6-8, using a standard trigonometric relationship,

$$D' = \frac{L}{\text{Cot}\,(\theta_2 + \Delta\theta_2) - \text{Cot}\,(180^o - \theta_1 - \Delta\theta_1)} \qquad (6\text{-}2)$$

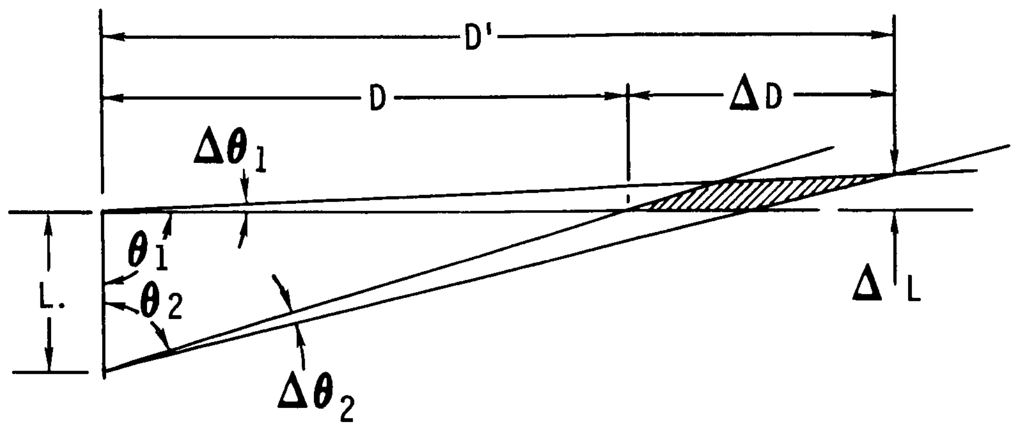



Figure 6-8 Ranging Uncertainty

Also

$$D = L \operatorname{Tan} \theta_2 \tag{6-3}$$

And

$$\Delta D = D' - D \tag{6-4}$$

Substituting and letting $\theta_1 = 90^o$

$$\Delta D = \frac{L}{\operatorname{Cot}\left(\operatorname{Tan}^{-1} \frac{D}{L} + \Delta\theta_2\right) - \operatorname{Cot}\left(90^o - \Delta\theta_1\right)} - D \tag{6-5}$$

Figure 6-9 contains plots of D versus ΔD for a system using a one-foot baseline and $1^o$ beams and for a system using a four-foot baseline and $0.1^o$ beams. Many combinations of transmitter beamwidth, detector field of view, and length of baseline are possible to produce curves between the ones shown.

System Signal-to-Noise Ratios — For a system as described above, the maximum range realizable depends first on sufficient energy being reflected with an adequate signal-to-noise ratio for detection. Second, the system must discriminate between objects illuminated by the transmitter beam and those illuminated from other sources.

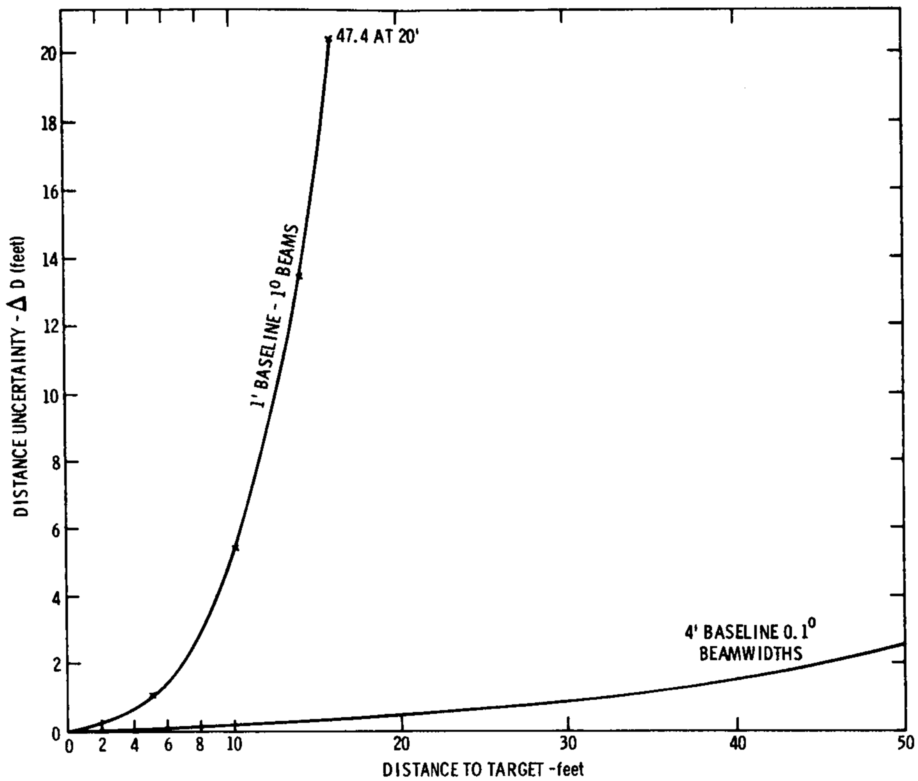



Figure 6-9 Range Uncertainty Versus Range

Discrimination is provided by two techniques. Use of a monochromatic source together with a narrow-band optical filter provides discrimination against light sources of other colors. However, this would not permit discrimination against sunlit objects which contain the same color. Further discrimination is accomplished by chopping the transmitter output at some frequency and filtering the detector output so as to pass only the signal at this frequency. In many cases, signal-to-noise ratio can be further increased by synchronous detection, i. e., passing only the detector output which is in phase with the chopped signal.

Signal-to-noise ratio will be defined as the ratio of receiver output with a diffuse reflecting object in the intersection of transmitter beam and detector field of view to receiver output with no object present.

Noise output with no reflecting object present is due to:

- Receiver electronics noise
- Detector noise
- Illuminated subjects in the detector field of view which are not in the intersection of the beams.

Energy Relationships — Assume that a diffuse reflecting object completely fills the transmitter beam and detector field of view as shown in Figure 6-10.

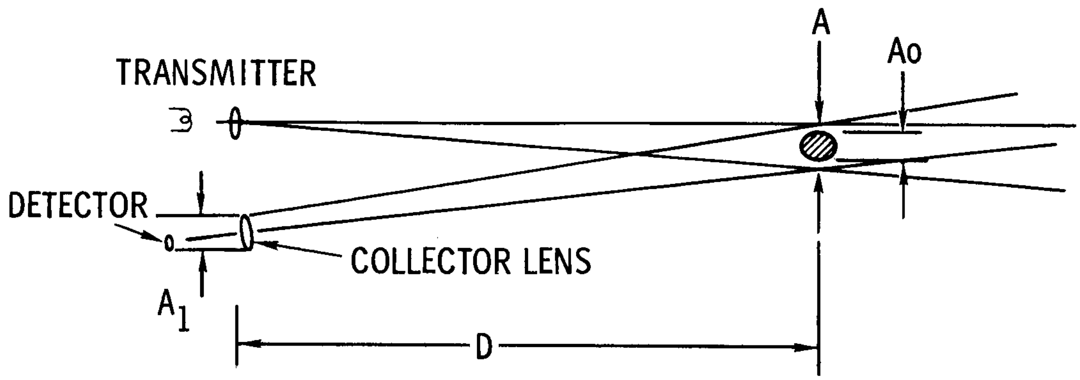



Figure 6-10 Energy Transfer Geometry

Where

| | | |
|---|---|---|
| $A_1$ | = | Detector collector area |
| $E_D$ | = | Signal energy received at the detector |
| $E_T$ | = | Transmitted signal energy |
| D | = | Distance from transmitter and detector to reflecting object |
| A | = | Maximum area of intersection of beams |
| $A_o$ | = | Effective reflecting area of object |
| K | = | Ratio of transmitted energy to that received at the collector when $A_o/A = 1$. This is a function of reflectivity and photometric function. |

Neglecting attenuation of energy by the intervening medium it can be shown that

$$E_D \approx \frac{E_T}{(D)^2} \times \frac{K \times A_o}{A} \quad (A_o \leq A) \tag{6-6}$$

If the area of the detector collector is changed from $A_1$ to $A_2$ then

$$E_D \approx \frac{E_T}{(D)^2} \times \frac{K \times A_o}{A} \times \frac{A_2}{A_1} \tag{6-7}$$

From Equation (6-7) it is evident that

- Energy received is proportional to collector area
- Energy received is proportional to transmitted energy

- Energy received is inversely proportional to object area when it is less than A
- Energy received is inversely proportional to $D^2$.

Figure 6-11 shows plots of signal-to-noise ratio versus range for an AC-DRL experimental system. It is assumed that the target fills the beam and that noise is constant. Measured signal-to-noise ratios at 48" on an oblique target were 10/1 for new white paint and 2/1 for blacktop. Extrapolated values are obtained using Equation (6-7) and assuming only D increases. However this system was not optimized for the application being discussed.

Let the signal level for a satisfactory S/N be a constant. Then the distance at which such a signal is achieved varies with $E_D$

$$D = K\sqrt{E_D}$$

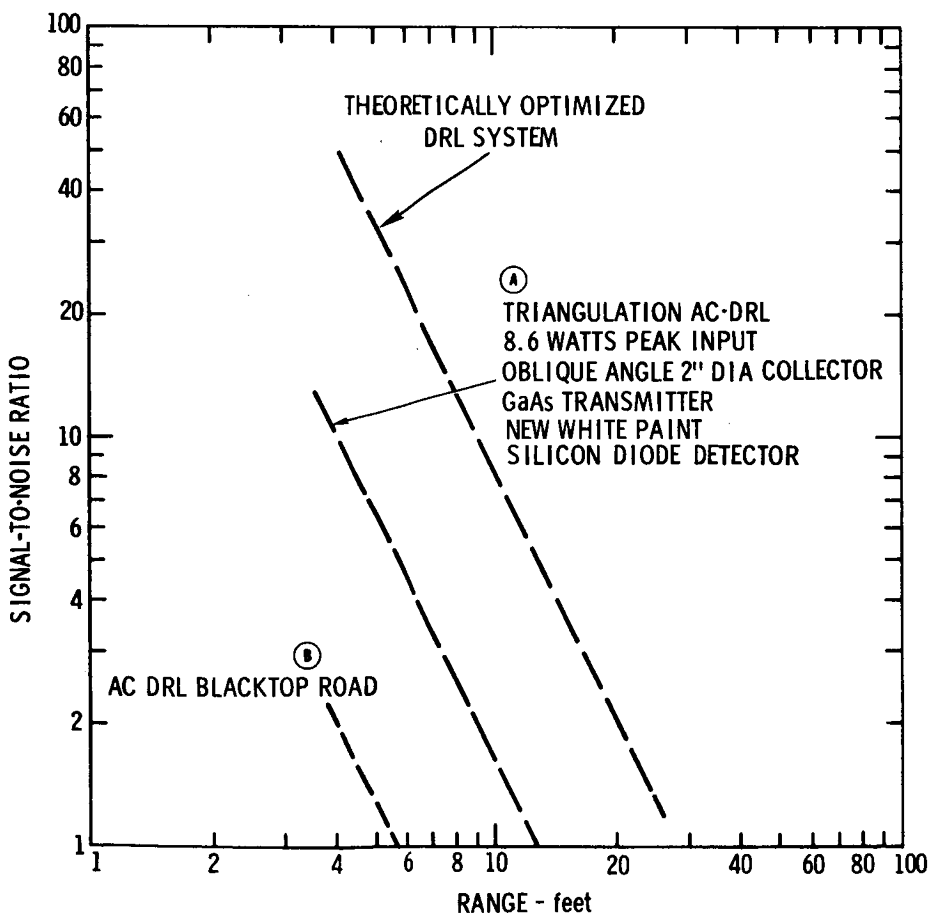



Figure 6-11 Signal-to-Noise Ratio Versus Range

The combination of transmitter and detector can be used in a number of configurations for terrain assessment.

1. A single transmitter and receiver could be used to detect a surface feature at one azimuth and elevation with respect to the vehicle. This would be most useful in connection with an imaging system or for emergency alarm.
2. An array of such devices could provide greater sampling of the volume in front of the vehicle. Such an array could consist of
   - multiple pairs of transmitters and detectors
   - multiple transmitters and a single detector
   - multiple detectors and a single transmitter

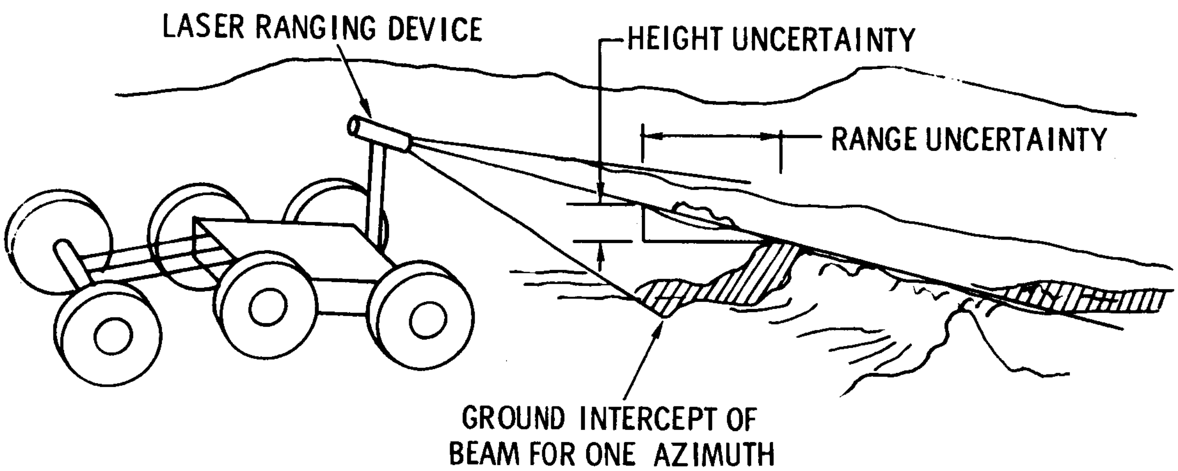
   Use of multiple transmitters and a single detector with a wide field of view is attractive because a large collector area is important. However, signal-to-noise ratio would be decreased.

   In all cases it would be necessary to discriminate between the returns from different beam intercepts to obtain knowledge of the terrain geometry. This could be accomplished by sequential operation or by using different transmitter pulse frequencies.
3. Azimuth and elevation of the intercept of beams from a single transmitter and detector can be varied to sense objects within a relatively thin vertical plane.

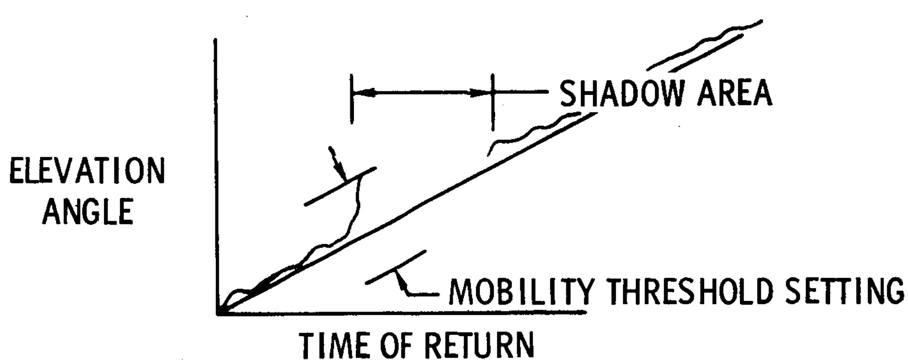
4. Azimuth, elevation and convergence of a single transmitter and receiver could be varied to sense objects within a volume.

(3) Split-Field and Coincidence Devices — Various split-field or coincidence-type ranging schemes could be incorporated into imaging systems. Since their operation depends on pattern recognition, they could not be easily automated.

(4) Automatic Appraisal — A class of possible devices would both sense terrain geometry and perform appraisal with respect to traversability. For RVMC, one is primarily interested in whether or not a proposed path toward some goal lies within the safe mobility capability of the vehicle. Knowledge of the nature, location, and size of each obstacle in the path is not usually required to make a decision.




a) Scanning Laser Ranging Device




b) Elevation Angle vs Time of Return

Figure 6-12 Pulsed Laser Ranging

Thus if a sensor can look at a potential path as a whole and determine on a go/no-go basis whether or not it is traversable, a few binary bits can be used to describe several paths as far as traversability is concerned. These can be used either for on-board or earth-based decisions. The limitations due to obscuration as discussed in Section 6.1.3.a, will, of course, still apply.

One such conceptual device would use a pulse ranging laser with elevation and azimuth scan over the field of interest. This is similar in concept to radar. However an image need not be recorded. Beyond some predetermined tolerance nonlinearity of the time of return of each pulse as a function of elevation would indicate that, for the particular azimuth, the terrain exceeds RV mobility capability. As shown in Figure 6-12(a) the uncertainty as to the height of surface deviations from a plane is a function of range resolution; range resolution is at least several inches at the present state of the art. As shown in Figure 6-12(b), a threshold detector can be set to sense hazards for each azimuth value.

A second conceptual device would utilize motion parallax to detect deviations of the surface from a plane. If two or more images are made from different vantage points, relative displacements of points in the images vary as a function of subject distances. If the images are formed with an open shutter while moving, the length of motion-blur of objects will vary with distance. This fact has led to a variety of concepts for automated photogrammetry. One is the synthetic aperture camera.(19) All such concepts suffer from certain theoretical difficulties in automating the process of forming an image (perhaps a profile or contour) of features at a given distance and at the same time removing multiple or blurred images at other distances.

However, it is also characteristic of an image formed in such a manner, that points at different distances move at different rates relative to one another during image formation. Thus if an image-forming device were pointed in the direction of vehicle travel, all surface points would move radially from the velocity vector as shown in Figure 6-13.

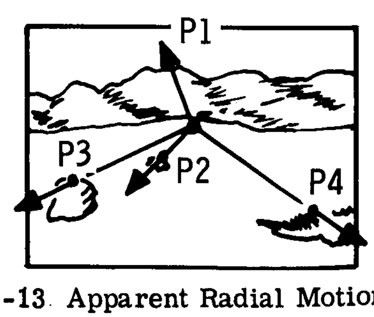



Figure 6-13 Apparent Radial Motion of Points

Image points would move at increasing rates as they became nearer. For any given radial line, the rates would vary with displacement of features from a flat surface. Thus spatial filtering techniques and frequency measurement might be suitable for detection of surface roughness exceeding some maximum value. Jitter of the vehicle velocity vector might require such a device to supply its own motion either while the vehicle was stopped or at a considerably faster rate than the vehicle if it were moving.

If a mask of one future path were placed as shown in Figure 6-14, the entire path would be evaluated as a unit.

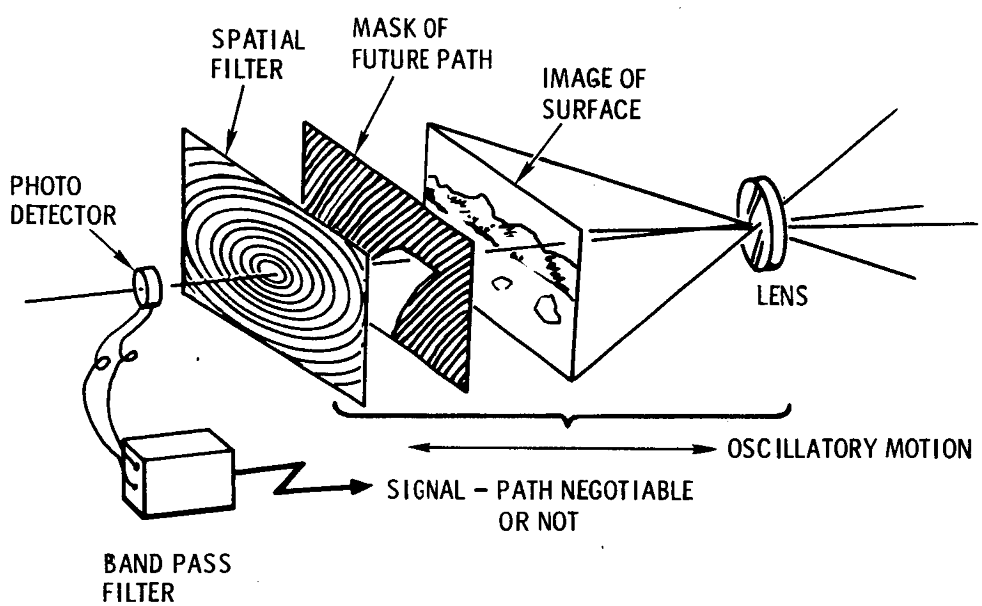



Figure 6-14 Conceptual Hazard Detector

For each possible future path as determined by steering positions a separate mask would be used. Thus for each path a go/no-go output would be provided as shown in Figure 6-15.

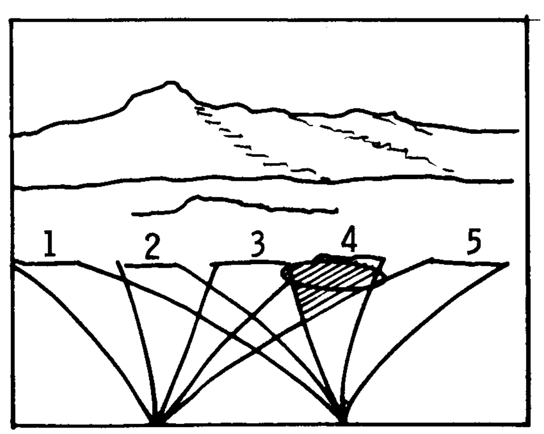



Figure 6-15 Coding of Hazardous Paths

If, for example, only path 4 is non-negotiable, the cross-hatched area contains a hazard and another path should be used.

The outputs from such a device could be used in several ways.

- On-board logic could choose a traversable path which most nearly fits the vector from the present position to the goal. The vector would be derived from dead reckoning data by the on-board navigation computer.
- High-quality images could be transmitted to earth and a tentative path to a goal chosen. During traverse the RV on-board logic would choose short-range paths as discussed above. This could be fully automatic or the few required binary bits could be transmitted to earth to form a coarse picture of terrain hazards relative to the original image.
- In step-by-step modes a low-quality monoscopic image could be transmitted to earth at each step together with the coded path assessment data. Superposition of the two in a display such as shown in Figure 6-15 would permit general evaluation of the terrain together with accurate assessment of negotiability. In theory this system would provide go/no-go outputs from very-high-quality inputs with the exception of occulted surface features.

c. Navigation Sensors. It will quite likely be necessary to know RV position accurately relative to a frame of reference based on surrounding surface features. Only secondarily is it necessary to know the location of such a reference frame relative to lunar or planetary coordinate systems. Therefore, in Table 6-4, techniques for determining RV position are divided into those relative to lunar and planetary coordinate systems and those relative to surrounding surface features.

DSIF tracking from earth requires no special equipment in space for the determination of the initial position of a RV relative to lunar or planetary coordinates. Initial position on the moon could be known within an area 400 meters[20] from inflight tracking and subsequent doppler information. Initial position on Mars would be known with somewhat less accuracy. How much less was not determined in this study.

Optical tracking, from earth, of a laser or solar reflector on the RV would permit accuracy of 40 meters in location with respect to both surface features and selenographic coordinates. This is a function of earth-based telescope resolution and would obviously be much poorer for Mars. Optical tracking would also be limited by atmospheric seeing conditions.

For the moon, correlation of orbiter information with surface features as observed from an RV would permit even greater accuracy. Location of the RV with respect to selenographic or areographic coordinates would then be primarily dependent on knowledge of the location of an orbiter photograph with respect to that coordinate system.

A celestial fix from the RV would require use of on-board equipment and at best would give location accuracy comparable to that obtained by this method on earth. Such accuracy, about one km, would probably not be suitable for traverses.

It seems likely that DSIF tracking is best for determination of initial position considering hardware requirements and the accuracy on initial position likely to be required for vehicle control. Correlation of surface-derived data with orbiter pictures is also promising if reliable techniques can be developed for identification of common points.

For determination of RV position relative to landmarks and/or previous vehicle positions, a combination of dead reckoning and measurements from surface features is a practical approach.

Dead reckoning position would be calculated from distance traveled as a function of wheel rotation and azimuth heading determined from an inertial heading reference or from a sun compass.

No existing pure inertial system appears to be practical because the accelerometers would have to operate in the low, nonlinear region of their operating curves. The necessity for periodic calibration would also pose a serious problem. The possibility should be looked at more carefully, however, especially in view of recent work in inertial components.

Although correlation of observed surface features with features in orbiter photographs may be practical for a lunar RV (assuming the ability to identify objects in both views) it is less likely to be practical for Mars because of the lower image resolution expected for Mars orbiters. In any case it would appear more useful as an auxiliary or backup mode rather than as a routine navigation tool.

In summary, then, it seems that DSIF position fixing is best for determination of initial position with respect to body coordinates. Dead reckoning, in combination with periodic fixes from surface features, appears suitable for positioning along the traverse.

d. Displays. The question of what display hardware to use on earth, while important, is best answered in the context of actual system design. More important in this study is to establish the nature of the required displays so that data processing and sensor requirements can be identified.

Many types of displays have been suggested in the various roving vehicle studies. In general they are direct photographic, or symbolic, or various combinations of the two. In addition one may hypothesize combinations of present and past pictures, panoramas, mosaics, plot plans, etc., incorporated in a control console or a control complex. To further complicate the analysis, one has a choice between stereo and monoscopic displays.

It is necessary to be exceedingly cautious in specifying such things as stereo panoramas complete with predicted paths, etc. This is because there is a large discrepancy between the information quality required for such a display and the state-of-the-art of the means of collecting and processing the information in the available time for RV control purposes.

Suggested types of integrated displays are listed in Table 6-11 together with their general applicability to fly-by-wire or automatic modes.

In addition to basic views of terrain, an integrated display may show

- RV attitude, possibly as an artificial horizon
- RV destination
- Predicted RV paths relative to terrain
- RV heading
- Photographic coverage (on plot plans)

Figure 6-16 is an example of a direct television image with a choice of predicted paths superimposed.[1] Figure 6-17 shows a purely symbolic computer-generated display. Figure 6-18 shows an integrated-type display where the picture might be either photographic or symbolic.

One advantage of the symbolic oblique view is that the RV may be shown together with features around it.

Table 6-11
APPLICABILITY OF DISPLAY TYPES

| Display Type | Data Source | Fly-by-Wire | Automatic |
|---|---|---|---|
| Photographic Oblique View of Terrain | Camera on RV | x | |
| Symbolic Oblique View of Terrain | Generated from oblique photos & other data received on earth | x | |
| | Coded on RV from imaging sensors | | x* |
| | Coded on RV from non-imaging sensors | | x |
| Photographic Plan View of RV/Terrain Relationships | Camera on RV photographing overhead mounted reflector | x | |
| | Orbiter photos | x | |
| Symbolic Plan View of RV/Terrain Relationships | Dead reckoning information from RV plus coded data from RV imaging sensors | x | x* |
| | Dead reckoning information from RV plus coded data from RV non-imaging sensors | x | x |

* Contingent on artificial intelligence developments.

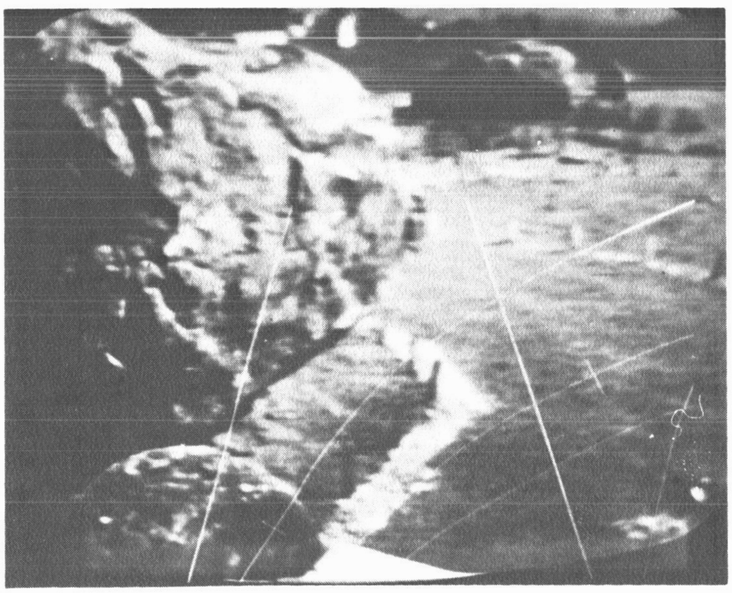


Figure 6-16 TV With Predicted Paths

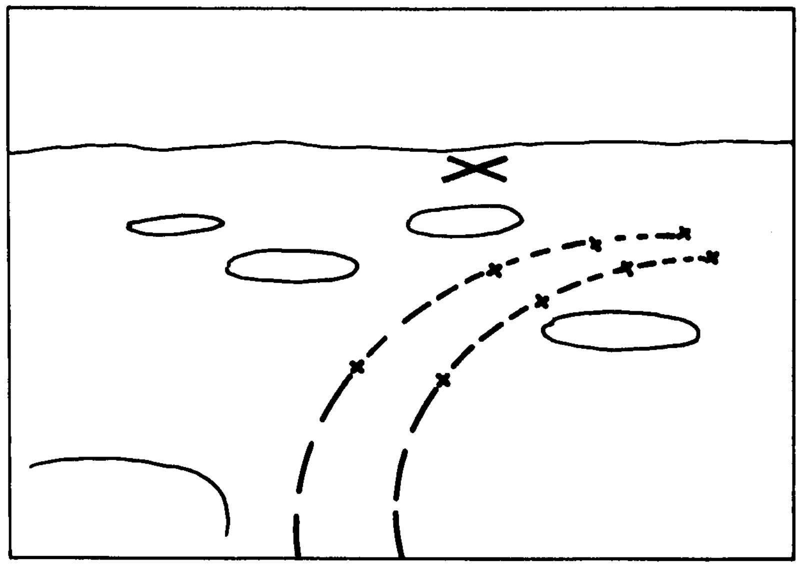


Figure 6-17 Symbolic Display

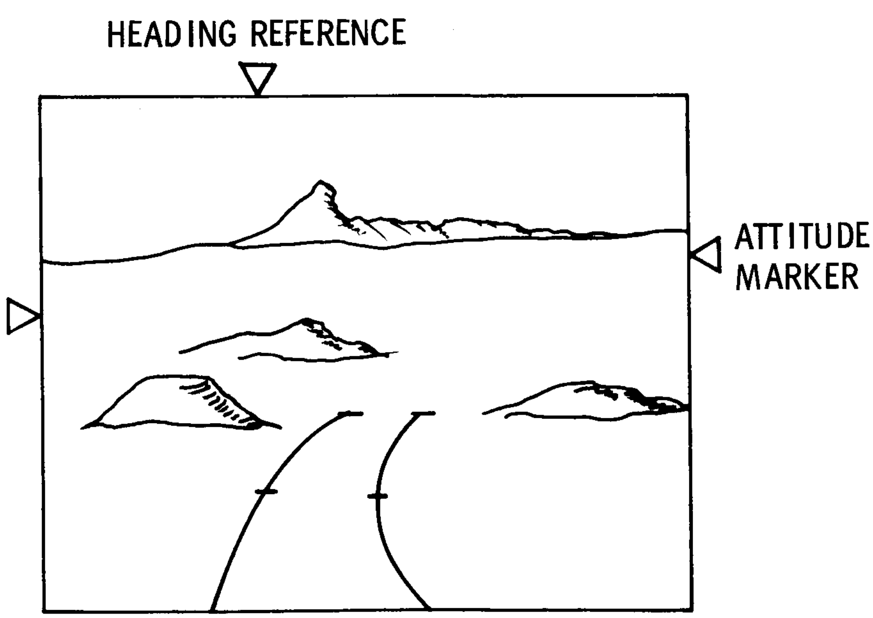



Figure 6-18 Integrated Display

e. Integration of Image Sensors and Displays. In a broad sense the function of a sensor subsystem is to collect and convey information concerning a quantity to the point where it is to be used for making RVMC decisions. The information quality depends on the cascaded parameters of sensors, data processing, data transmission, and output displays.

The design is straightforward for digital data representing quantities such as temperature. For video data many cascaded effects enter in. Video system parameters expressed in terms of the output display are, for detection of terrain features,

- Field angles
- Resolution
- Contrast
- Signal to noise ratio
- Frame rate
- Ease of stereo fusion

and for stereo measurement

- Geometrical fidelity
- Ratio of length of stereo baseline to subject distance.

Requirements for each one of these parameters should be established on the basis of a realistic balance between the parameters of each piece of equipment and procedure in the chain. As an example, the finest video system is useless for stereo evaluation if the stereo baseline is either too great or too small for a particular subject and distance.

Figure 6-19 shows functional block diagrams for some existing space imaging systems. In Figure 6-19(a) a two-dimensional image is formed and stored on a vidicon faceplate. The faceplate is scanned with an electron beam, and the one-dimensional signal is transmitted simultaneously. The image is erased, and the process is repeated for the next frame. This method has been used on Ranger and Surveyor and has been proposed for a modified Surveyor for Mars by Hughes Aircraft Co.(21)

In Figure 6-19(b) a 2-D image is formed and stored on a vidicon faceplate. The faceplate is scanned with an electron beam and the 1-D signal stored for later transmission. The image is erased and the process repeated for the next frame. This was used on Mariner IV and was proposed for a Mars Orbiter by The Boeing Company.(22)

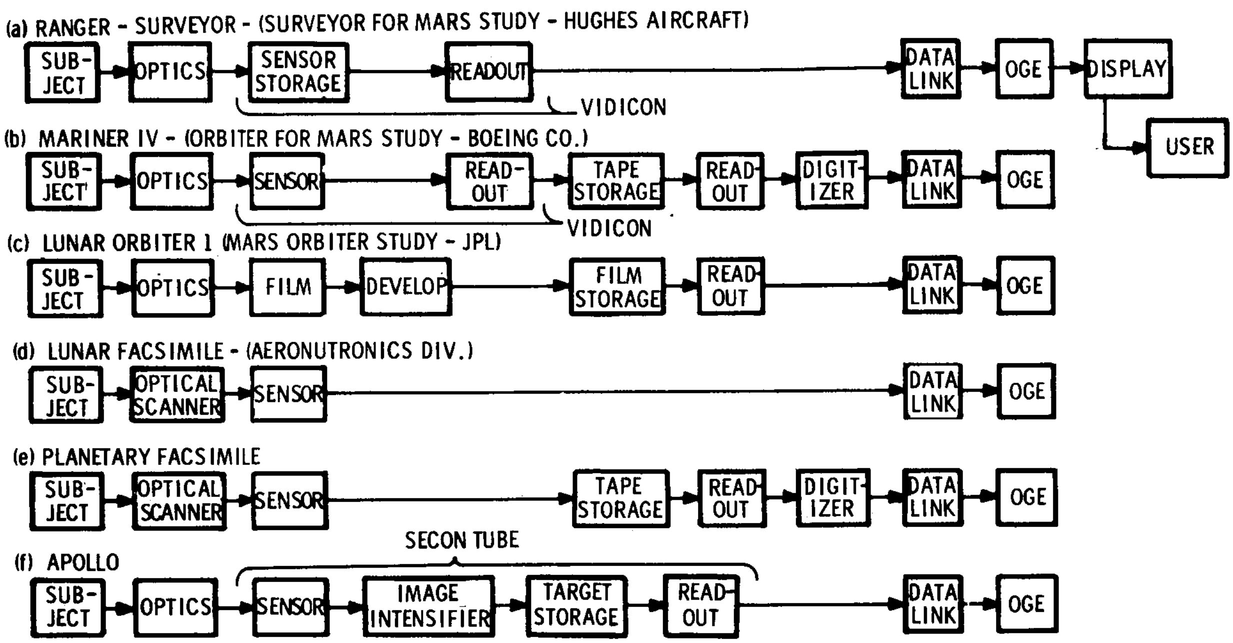



Figure 6-19 Existing Space Imaging Systems

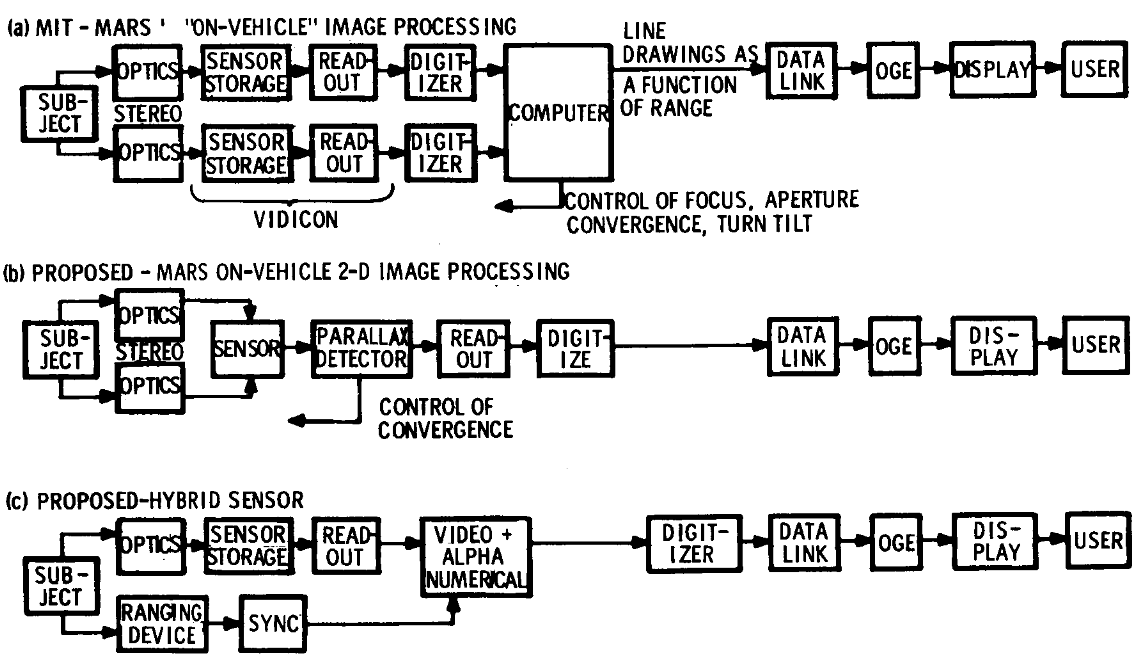



Figure 6-20 Proposed Space Imaging Systems

In Figure 6-19(c) a 2-D image is formed on film. The film is developed and placed in storage for later readout. It is read out by electro-optical-mechanical scanning (CBS Photoscan System) and simultaneously transmitted. It is used on Lunar Orbiter and has been proposed for a Mars Orbiter by JPL.[23]

In Figure 6-19(d) the subject is scanned point by point with an optical/mechanical scanner and sensed with a photosensitive device. The resulting 1-D signal is simultaneously transmitted. This system has been developed by the Aeronutronic Division of Philco-Ford Corp.[24] Some space missions may not permit transmission at the same rate or at the same time the subject is being scanned. In this case a buffer storage could be added as shown in Figure 6-19(e). In this case, digitizing could be done before storage.

Figure 6-19(f) uses the Westinghouse Secon camera tube for the Apollo system. It incorporates an image intensifier for sensitivity to low light levels. Whereas the Surveyor uses time integration for imaging with Earth shine illumination, Apollo will require a higher frame rate and thus greater sensitivity.

All of the systems shown in Figure 6-19 could have a data compression block added. Basically, data compression permits transmission of information with more efficient use of power and bandwidth.

A strip mapping type of imagery could be accomplished in many ways. The imaging system would provide a scan of the subject in one dimension and vehicle movement would provide the scan in the other dimension. This would have the advantages of lengthening image acquisition time and of providing a continuously developing image of the terrain being traversed. Disadvantages are that images are spatially incoherent without the use of sophisticated corrections for variations in orientation of the camera platform and that a fairly straight line path would probably be necessary. A hybrid system with an option of normal scanning or strip-map-type scanning might have advantages, since during motion, a nonredundant strip map could be generated.

In addition, there are many approaches to reducing the amount of information to be transmitted by pre-processing of video or other data. Figure 6-20 shows the MIT system[12] where the output of a pair of stereo television cameras is processed in an onboard computer. The computer performs such functions as contrast enhancement, contour detection and stereo interpretation both to control the vehicle and to provide simplified visual information for transmission to earth.

In this system analysis is based on information which is one-dimensional and which has undergone degradation due to television distortion, sampling, etc. In theory, at least, stereo comparison and contour outlining could be done at the point where the image is still two-dimensional. This would permit production of much higher quality range and other information. One such configuration is shown in Figure 6-20(b).

Figure 6-20(c) shows a hybrid configuration. A ranging device of high accuracy is used to provide information to be superimposed on a video image of much lower quality than that which would be required of a stereo pair for determination of range on earth.

## 6.2 DATA PROCESSING AND LOGIC, SPACE-BASED

### 6.2.1 Fly-By-Wire Modes

In the fly-by-wire mode, most sensor data are transmitted to earth and most appraisal and decision processes are carried out by human beings. Nevertheless, data processing and logic functions are required on the vehicle to insure efficient use of the data link, to carry out command sequences, and to directly command emergency actions as indicated by signals from protective sensors. Because of constraints on the rate of video and other data transmission from exploratory missions on the moon and particularly the planets, it is necessary that only required information be transmitted and that this be done in the most efficient manner possible.

The large number of studies directed toward this end are in the two areas of minimizing the amount of data to be transmitted and of data compression.

Minimizing the amount of video information to be transmitted can be accomplished by preselection and preprocessing.

Kortman[25] has classified data compression techniques under parameter extraction redundancy reduction (e.g., of picture elements) and statistical encoding (e.g., of grey levels).

a. Preselection. It is obvious that selection of video quality, field angle, and selection of which pictures are to be transmitted is an effective way to maximize information flow and minimize transmission requirements. At present this is done by earth command or by preprogramming picture sequences. For remote vehicle control, automatic decision-making logic could be incorporated into the vehicle.

First, the number of picture elements or grey levels could be varied. From some minimum number of picture elements, for vehicle control, an increase is indicated when objects of interest subtend less than, say, 16 picture elements. An increase in the number of grey levels is indicated when undesired contouring due to grey-level quantizing appears on large objects.

Second, the field angle can be varied. One typical criterion would be that, for straight-line vehicle motion, a smaller field angle is required to encompass the future path than for a curved vehicle path.

Third, video should be transmitted only when warranted by terrain characteristics or mission needs. For example, on relatively smooth surfaces, as established by non-imaging sensors, the vehicle might be caused to progress without transmitting video data.

b. Preprocessing. One type of video processing prior to transmission which is within the state of the art is the formation of composite images from various sensor data. For example, the output of an optical rangefinder could be synchronized to appear at the corresponding location on a video image. This would permit a low-quality picture to be transmitted instead of high-quality stereo pairs for measurements beyond a few feet.

A second type of preprocessing involves pattern recognition and decision making on the vehicle. Although this is not yet practical, intensive investigations by many groups (such as those at AC-DRL, MIT, RCA, and elsewhere) show promise for this approach.

A third type involves analog preprocessing to reduce grey-level requirements without the addition of quantizing noise. One way of doing this is to reduce low-frequency response over each scan and to increase the gain so that high frequencies, which contain most of the visual information, are emphasized.

c. Data Compression. Data compression techniques applicable to the processing of video are reduction in redundancy of picture elements and reduction of grey-level requirements by encoding. These and other approaches are the subject of intensive investigation by many groups.

Most of the experimental results were reported to have been done by simulation where communication link problems were not experimentally investigated.

Element compression ratio (ECR) is defined by Kortman[25] as "the ratio of the number of data values presented at the input to the number of significant data values delivered to the buffer memory during a specific time value." He defines bandwidth compression ratio (BWCR) as "the ratio of the number of bits presented at the input to the number of bits delivered at the output of the data compressor. This ratio includes all penalties for identification, timing, and synchronization and is therefore a true measure of overall compression efficiency."

It is possible, from this and other reports, to draw preliminary conclusions concerning the future usefulness of data compression for remote vehicle control.

- Data compression for images may provide bandwidth compression ratios varying from 2 to perhaps 5 or 10. This is dependent on the nature of the subject, signal-to-noise ratio, and required picture quality.
- Data compression is accomplished at the cost of added equipment and complexity on the vehicle as well as at the receiving end.
- Redundancy reduction techniques give poor results at signal-to-noise ratios much below 30 dB.
- Data compression may be very useful for transmission of engineering and other intermittent type data.

### 6.2.2 Automatic Modes

In the semiautomatic and fully automatic modes, the vehicle is more or less isolated from the earth and the control appraisal and decision functions are performed by on-board equipment, designated in Section 5 as the Master Control Logic. The mission control center plays a supervisory role in the semiautomatic mode and a monitoring role in the fully automatic mode.

In the semiautomatic mode, illustrated in Figure 5-6, all information processing functions for routine commands are located on the vehicle, i.e., the vehicle appraise-and-decide equipments make velocity and steering choices based upon terrain obstacle, vehicle attitude, and goal information inputs. An operator at SFOF makes global checks of performance, analyzes problems beyond the capability of the RV, originates new goals, and updates the memory bank. The appraise-decide capabilities of the guidance and control system might be stated as follows:

1) Must be able to relate goal data to the millieu in which the RV works.
2) Must be able to assimilate terrain obstacle data and assess hazards.

3) Must be able to select a safe sequence of steps for closing the gap between the RV and the goal.
4) Must be able to recognize when a situation is too complex for an adequate response and put the system into a protective mode.

A given control system might have a command repertoire consisting of the following motion commands.

1. Forward
2. Reverse
3. Steer right – partial
4. Steer right – full
5. Steer center
6. Steer left – partial
7. Steer left – full
8. Brake.

These commands can occur in combinations, but not all combinations are logical, e.g., forward and reverse. Table 6-12 identifies with a 1 those which are logical. (In addition there are, of course, commands associated with the antenna and the sensors.) The function of the Master Control Logic is to assimilate a great amount of input data, largely stochastic in nature and changing in character with time, and to arrive at "optimal" choices of commands from the limited repertoire available. This immediately implies the existence of a criterion of optimality against which any possible choice might be measured. Because of the limitless diversity of possible inputs it would be impossible to preprogram a unique response for each possible input stimulus. With a human, as in the fly-by-wire mode, intuition and subjective judgment can play a major role in the decision process. With a machine, the inputs must be described explicitly and quantitatively.

A sizable literature is accumulating in the fields of automatic, adaptive systems, learning systems, and self-organizing systems. It would appear that some of this might have very fruitful application to the appraisal/decision processes in the RVMC automatic modes. However, much of the work is still very theoretical and deals only superficially with the practical aspects of implementation. It does seem clear, though, that the data processing requirements can be imposing unless some more subtle approach is taken. An example of this might be the automatic appraisal sensor approaches described in Section 6.1.4.b(4).

Table 6-12
LOGICAL COMBINATIONS OF DECISION OUTPUTS

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Forward | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Reverse | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| Brake | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Stop | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

### 6.2.3 Data Storage and Logic Equipment, State of the Art

Indicative of the present state of the art for data storage and logic equipments is the Apollo guidance computer.[26] This computer system consists of memories, an adder, instruction decoder, memory address decoder, and seven addressable registers. The computer can execute 40,000 instructions per second. Table 6-13 lists the Apollo computer characteristics.

Instructions can address registers in either the fixed or the erasable memory. Each memory word has 15 information bits and a parity bit. Data are stored as 14-bit words with a sign; instruction words have three order-code bits and 12 address-code bits. The normal sequence of instructions can be broken by a number of involuntary sequences, which are not under normal program control. These are triggered either by external

Table 6-13
COMPUTER CHARACTERISTICS FOR APOLLO GUIDANCE

| | |
|---|---|
| Word transfers | Parallel |
| Word length | 16 bits = 15 data + 1 parity |
| Number system | Modified one's complement |
| Memory cycle time | 11.7 μsec |
| Fixed memory | 36,864 words |
| Erasable memory | 2,048 words |
| Normal instructions | 34 |
| Involuntary instructions (interrupt, increment, etc.) | 10 |
| Interrupt options | 10 |
| Addition time | 23.4 μsec |
| Multiplication time: 14 x 14 bits | 46.8 μsec |
| Double-precision addition time | 35.1 μsec |
| Increment time | 11.7 μsec |
| Number of counters | 29 |
| Power consumption | Less than 100 watts (including two DSKY's) |
| Weight | 58 pounds (computer only) |
| Size | 1.0 cubic foot (computer only) |

events — an astronaut's entering data from the keyboard, for instance — or by certain overflows within the computer.

Computer words flow over prelaunch and inflight radio links between the computer and ground control. The downlink rate is 50 words or 800 bits per second. During one memory cycle the interface stores a full 16-bit word in a flip-flop register; upon command, it sends the bits serially in a burst to the communications system of the spacecraft. Each bit received on the uplink requires a memory cycle; the maximum rate is 160 bits per second.

Each of the Apollo computer memory's six modules stores 98,304 bits of information. The core rope memory has a bit density of approximately 2000 bits per cubic inch, including all driving and sensing circuits, interconnections, and packaging hardware.

6.2.4 Future Trends in Data Storage

The results of an RCA survey[27] of advanced storage techniques have been tabulated in Table 6-14. Storage densities of 3000–6000 bits per cubic inch, including the same functional hardware as for the Apollo core rope memory, may be achievable in three to five years.

Table 6-14
SURVEY OF ADVANCED STORAGE TECHNIQUES (REFERENCE 27)

| Type | Adequate for Video Storage | Power Consumption | Storage Density (Bits/in.$^3$) (Excluding Electronics) | Volume For $2 \times 10^6$ Bits (cu. in.) (Excluding Electronics) | Volume Electronics For $2 \times 10^6$ Bits (in.$^3$) | Total Weight For $2 \times 10^6$ Bits (lb) |
|---|---|---|---|---|---|---|
| Ferrite Memories | | | | | | |
| a) Toroid | Yes | Low | 2,000 | 1,000 | 500 | 50 |
| b) Bead | Yes | Low | 8,000 | 250 | 500 | |
| c) Apertured Plate | Yes | Low | 10,000 | 250 | 500 | |
| d) Laminated Sheet | Yes | Low | 20,000 | 200 | 500 | |
| e) Film | No | | | | | |
| f) Flute | Yes | High Peak | 8,000 | 250 | 500 | |
| g) Waffle-Iron | Yes | High Peak | 10,000 | 250 | 500 | |
| Magnetic Metal Memories | | | | | | |
| a) Twister | No | | | | | |
| b) Thinfilm | Yes | Low | 50,000 – 500,000 | | | |
| c) Permalloy Transfluxer | Yes | Low | | | | |
| Cryogenic Memories | | | | | | |
| a) Wire-Wound Cryotron | No | | | | | |
| b) Thin Film Cryotron | No | High | | | | |
| c) Cryosar | Yes | | | | | |

Another writer[28] has predicted a 200-fold increase in data processing speed and a reduction in size by a factor of 1000, together with substantial improvements in reliability over the next ten years.

## 6.3 DATA PROCESSING AND LOGIC, GROUND-BASED

In this section, existing facilities for handling of data are compared with that which is needed for remote vehicle control.

Figure 6-21 shows the video data flow for Ranger, Mariner IV, Surveyor, and Lunar Orbiter. The Surveyor configuration produces the most comprehensive results and is also probably nearest to fulfilling remote vehicle control requirements. DSS 11 at Goldstone, California, includes the On-Site Data Recovery Subsystem (OSDR) and the On-Site Film Recorder Subsystem (OSFR). The OSDR includes a videotape recorder and the OSFR includes a 70mm film recorder.

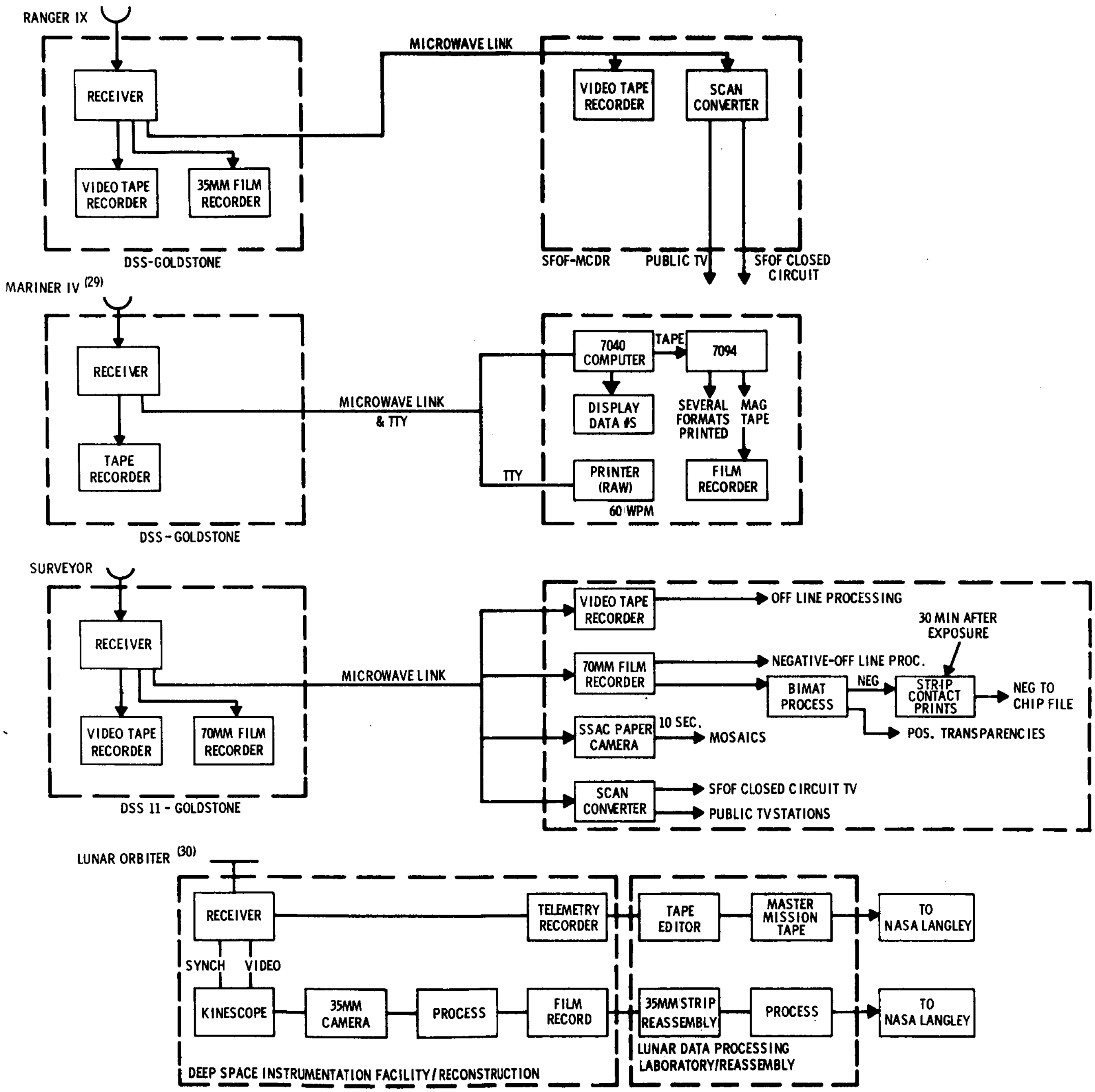



Figure 6-21 TV-GDHS

At SFOF, for the Surveyor program, is included a Media Conversion Data Recovery Subsystem (MCDR) and a Media Conversion Film Recorder Subsystem (MCFR). The MCDR includes a video tape recorder and the MCFR includes a 70mm film recorder.

It is evident that the type of system outputs (electronic images, positive and negative transparencies, and paper prints) would be suitable for almost any remotely controlled vehicle application. However other factors enter in, such as processing speed and geometric quality for terrain assessment.

### 6.3.1 Fly-By-Wire Modes

In addition to the existing facilities described above, it may be necessary to have on-line equipment and procedures for

- Data decompression
- Photogrammetry and photometry
- Generation of integrated control displays
- Navigational computations and path plotting
- Logic associated with command sequences (probably an adaptation of present software)
- Image enhancement, noise removal, distortion removal.

One way of organizing data and video flow for both automatic landing and human use is by use of a unit video document.(a film chip on a punched card). Figure 6-22 is a block diagram of the data flow for such a system.

The distortion removal sub-loop might also include removal of systematic noise and image enhancement. However, for purposes of near real-time RV control, it appears feasible and desirable to avoid these functions. Density variations from line to line in the image can be greatly reduced for improving qualitative interpretation by reducing the low frequency response of the film recorder. For stereo measurements up to a few feet from the vehicle, image geometrical distortion is not critical.

Figures 6-23 and 6-24 are block diagrams of the navigation and control areas.

### 6.3.2 Automatic Modes

In these modes earth data processing and logic will be used more for fulfilling a monitoring and supervisory function. Therefore real-time or near-real-time processing

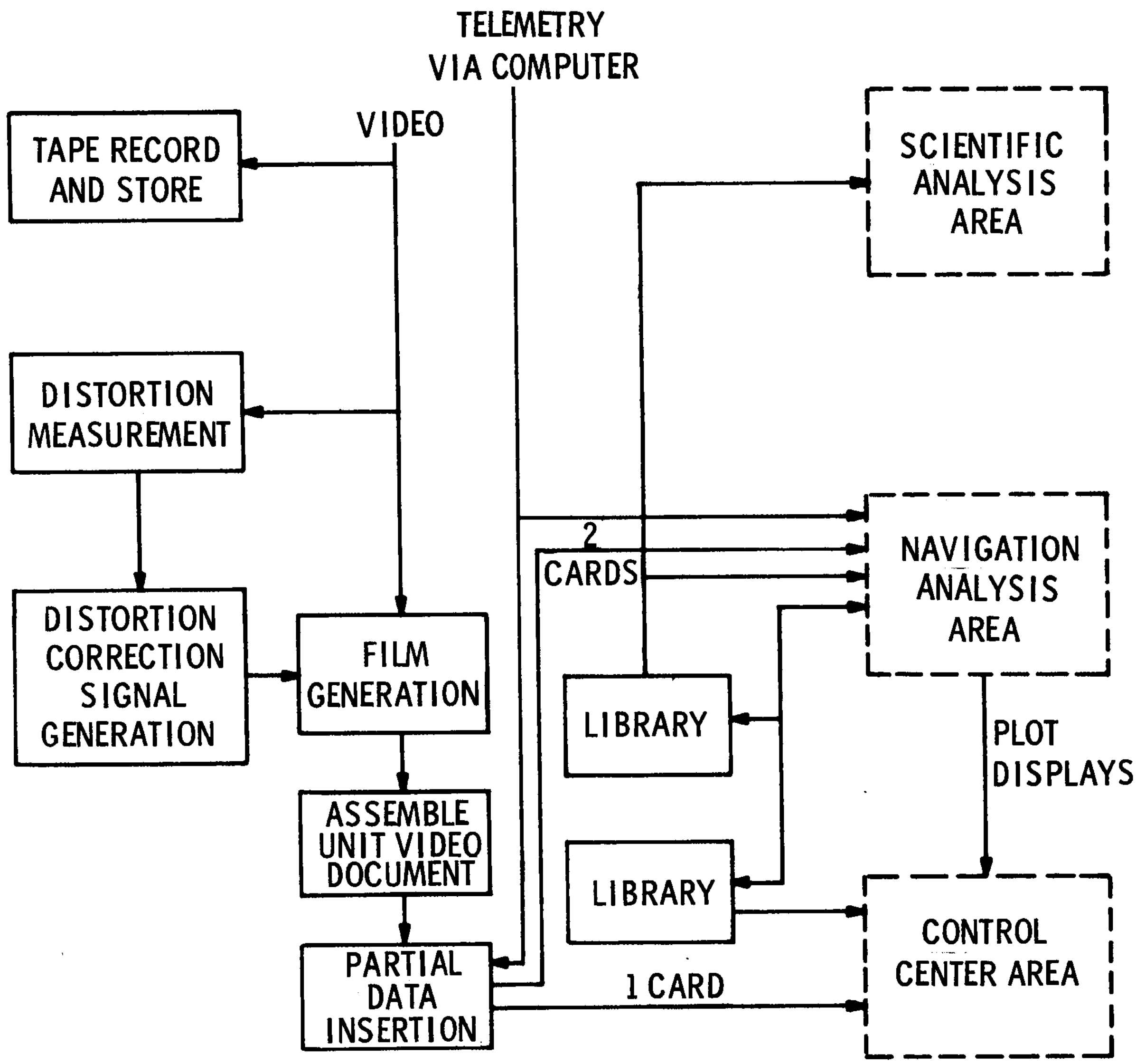



Figure 6-22 Data Handling Block Diagram

of data and video will not be critical for step-by-step control of the vehicle. While the data flow shown in the previous section would still be required, the necessity for automation and processing speed would be reduced.

## 6.4 MOBILITY SUBSYSTEM

The mobility subsystem of the roving vehicle must be considered as an element of the motion control system in the sense that, as weight is allocated to greater mobility (especially as measured in terms of hazard negotiation), requirements placed on the rest of the system for detecting and measuring hazards may be relaxed. There is thus a weight tradeoff possible between basic mobility and the complexity and weight that must be incorporated in the control function.

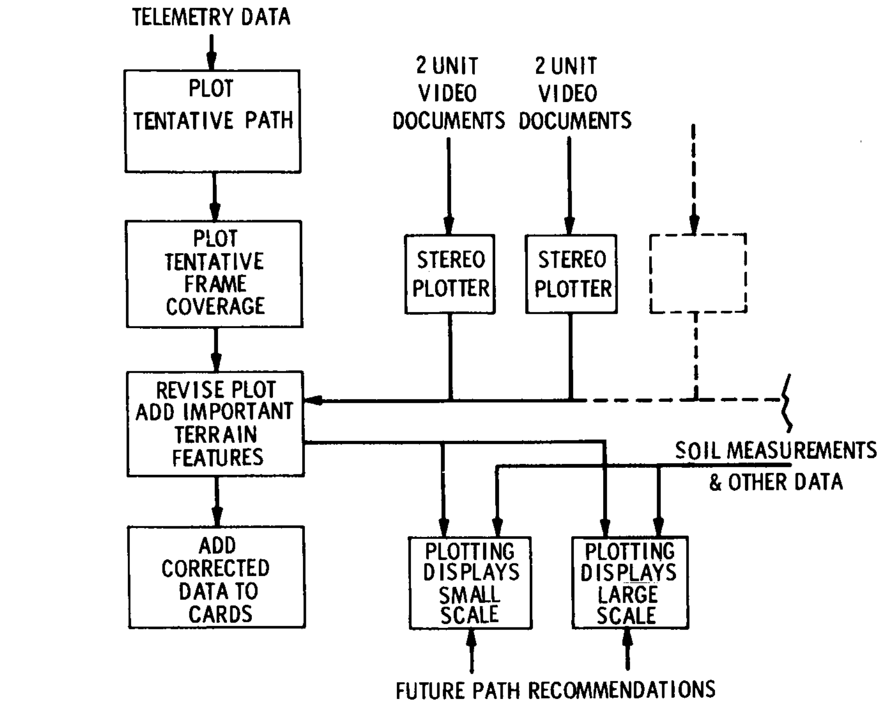



Figure 6-23 Navigation Plotting

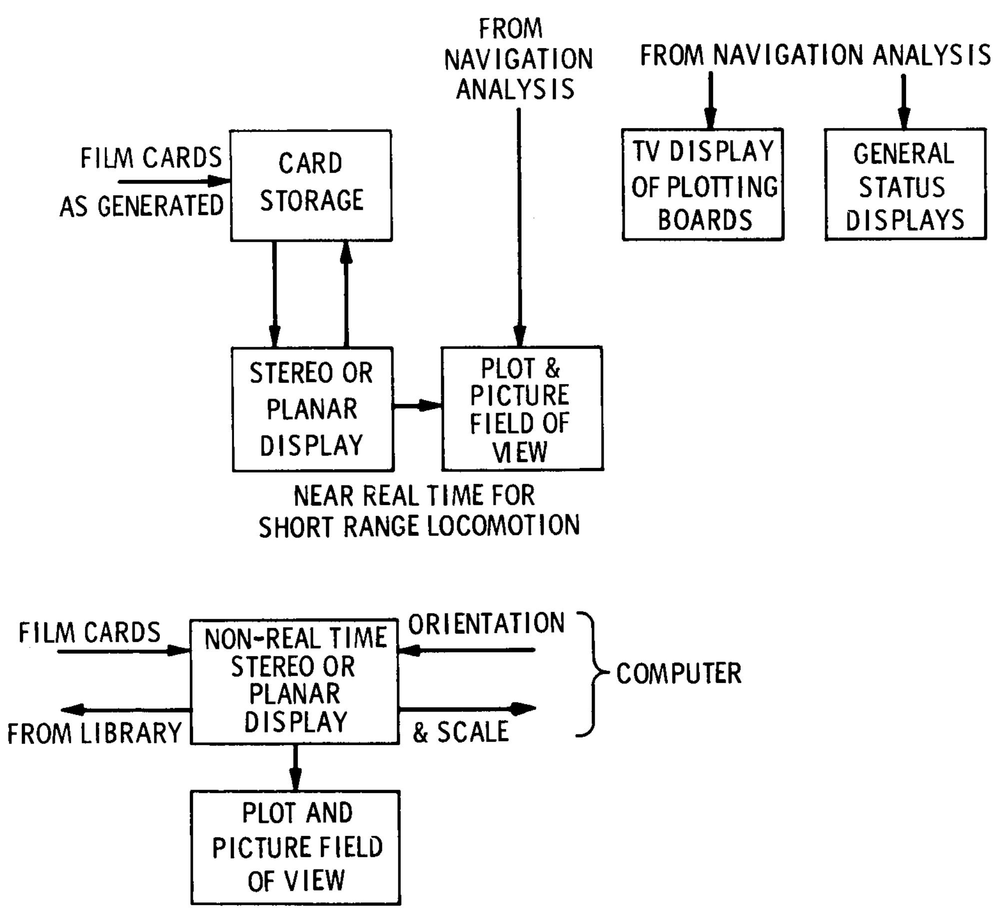



Figure 6-24 Control Center Displays

Vehicle capability may be described in terms of several variables, the most significant of which are:

1) Obstacle Capability
   a) Step height
   b) Crevice width
2) Maneuverability
   a) Turning radius
   b) Off-tracking or encroachment
3) Stability
   a) Static
   b) Dynamic
4) Gradeability
5) Locomotion energy
6) Payload-to-gross-weight ratio.

Obstacle capability, maneuverability and stability depend mainly on the geometry of the mobility subsystem, while gradeability (or ratio of drawbar-pull to weight) and locomotion energy are most closely related to the gross weight, but also depend to a great extent on the degree to which one is willing to compromise overall mobility performance.

Many other factors ultimately affect the mobility performance of a vehicle in adverse terrain. Perhaps one of the most significant is the capability to avoid impediments which would normally be negotiable, but which could cause termination of the mission if encountered in certain ways or in certain combinations. For example, small rocks can jam wheels, or outcroppings can become entangled in structural members. Although this type of mobility performance may be crucial to mission success, it is difficult to evaluate quantitatively. It results mainly from careful attention to such considerations in the design process.

Attempts have been made in the past to derive a point-valued measure of the mobility performance of vehicles – a mobility "index" or "figure of merit" – which subsumes all of the important performance parameters under one number. Such attempts have not generally been very satisfying because they usually involve the a priori assignment of normalizing functions and weighting factors. The results are often sensitive to the arbitrary values assigned to these weightings and normalizations, and are useful only when related to specific missions for which these priority assumptions hold. For this reason, no such index of performance is used in this study. In the RVMC study the interest is in a broad spectrum of vehicles to perform a variety of missions in a variety of environments. When the importance of specific performance parameters to the control function is better understood, it might be possible to derive a "control index of mobility performance," but such a figure would probably be of doubtful value.

### 6.4.1 Conventional Vehicles

a. Rigid Frame

A rigid-frame four-wheel vehicle has the advantage of being less complex and more reliable than a flexible or articulated-frame four-wheel vehicle. It does, however, have less stability, controllability, and ride qualities on undulating terrain. Its mobility capability for steps and crevices will be the same. For six-wheeled vehicles the simplicity of a rigid-frame design is overbalanced by the much greater mobility of a flexible-frame vehicle. From preliminary design work at AC-DRL and elsewhere it appears that a rigid frame is preferable for 4-wheel vehicles and a flexible frame for 6-wheel vehicles, other factors permitting.

b. Articulated Vehicles

To provide a basis for trading off the weight and performance of mobility subsystems against the weight and performance of other components of the RVMC system, a survey was made of vehicles which have resulted from reasonably thorough preliminary design efforts at AC-DRL. All of these vehicles were designed for specific missions and delivery systems and all are intended for lunar operation. The designs reflect, to some extent, features which are peculiar to those missions and delivery systems and the comparison therefore is not strictly on a common basis. Nevertheless, they comprise a useful basis for characterizing the performance, weight, and size relationships of roving vehicles for purposes of the RVMC study. Because of the relatively greater accessibility of good data on vehicles having six wheels, this is the type used for all data points in this survey.

Four such vehicles have been used to characterize a broad spectrum of gross weights ranging from 100 pounds to 24,000 pounds. The largest vehicle was not carried through a preliminary design, but has been included to show the trends beyond the range of vehicles that have been through a preliminary design.

Table 6-15 shows the important design data for the four base vehicles of the survey. The dimensional relationships are plotted in Figure 6-25. Overall length has arbitrarily been chosen as the common independent variable. It is seen that all dimensions scale approximately proportionately, except tread and overall width. In the absence of form factor constraints, one would expect geometric similarity. The lack of proportionate scaling for width and tread among these vehicles does, in fact, arise from the envelope constraints which were imposed. In the absence of such constraints, an overall width-to-length ratio of about 40–60 percent is a reasonable compromise, as shown by the dashed lines in Figure 6-25.

Table 6-15
VEHICLE DESIGN DATA

| Vehicle Description | O/A Size (in.) | | Wheel Size (in.) | | Wheel Base (in.) | | Tread (in.) | Gross Weight (lb) | Mobility Weight (lb) | Payload Weight (lb) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Length | Width | Dia. | Width | Front | Rear | | | | |
| SLRV Phase I | 72 | 30 | 18 | 6 | 27 | 27 | 24 | 85.1 | 26.4 | 58.7 |
| Specified LSSM | 160 | 92 | 40 | 10 | 58 | 62 | 82 | 2,000 | 590 | 1,410 |
| MOLAB | 242 | 125 | 60 | 15 | 87 | 95 | 110 | 7,166 | 1,240 | 5,926 |
| AC-DRL Saturn V Concept | 576 | 204 | 144 | 30 | 216 | 216 | 174 | 24,000 | 8,300 | 15,700 |

Under the assumption of geometric similarity, only one characteristic dimension is needed to describe the size of a vehicle. Figure 6-26 shows the manner in which gross vehicle weight varies with the overall length, overall width, and with the product of length by width for the four vehicles considered. Least-square linear fits in each of the three cases yield relationships of the form

$$\text{Weight} = K\,X^N$$

where X is the independent variable (length, width, or length-by-width product), and K and N are parameters.

Of the three cases, the relationship between gross weight and width shows the least variance and follows a cube law as follows:

$$\text{Gross weight} = 3.33 \times 10^{-3}\,(\text{width})^3$$

where weight is in pounds and width is in inches.

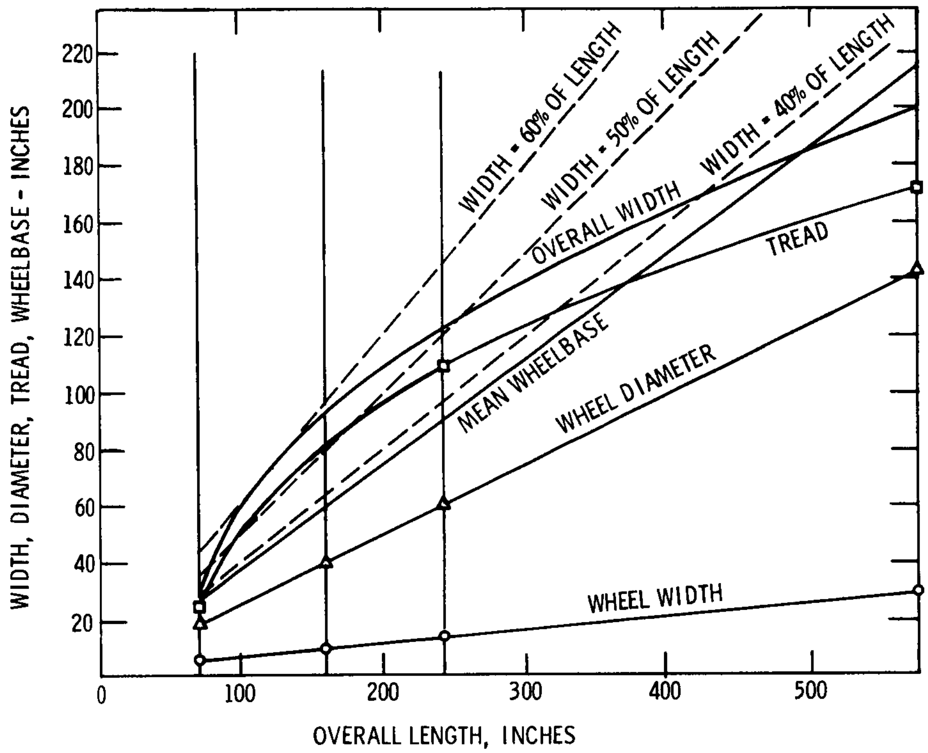



Figure 6-25 Dimensional Relationships of 6 x 6 Lunar Vehicles

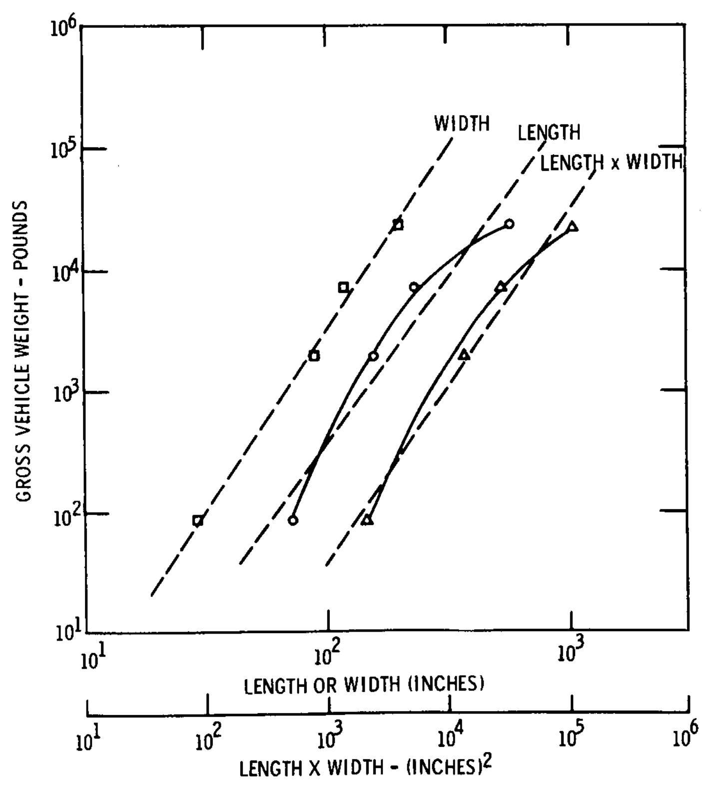



Figure 6-26 Relationship Between Weight and Size

This relationship cannot, of course, be adopted as completely general, since the weight is obviously not independent of overall length. For vehicles where the width is between 40 and 60 percent of the length, though, it is probably useful for preliminary estimates.

From the data in Table 6-15, the relationships between gross weight, mobility subsystem weight, and payload weight may be noted. Here it is assumed that the mobility subsystem weight consists of the following components: chassis-frame, wheels, wheel drives, steering, axles, structures and/or compartments to which payload items are attached, and fenders and suspension components, when used. No weight is included for power or energy associated with locomotion, since this is quite mission-sensitive.

For the four vehicles, the gross weight breaks down into payload and mobility as shown in Table 6-16. One sees that for lunar vehicles the mobility subsystem constitutes about 30 percent of the gross weight. The apparently anomalous situation in the case of the MOLAB arises from two main considerations:

(1) The MOLAB provided an enclosed "shirtsleeve" working environment in a cylindrical shell. This shell provided some of the structural functions normally performed by the chassis, yet its weight was charged to crew systems.

(2) MOLAB wheel drive weights were based on an early design and early performance requirements. Subsequent experience with the design and increased performance requirements caused increases in the weight of later designs of wheel drives of this type.

As explained below, the 30% of gross weight allocable to mobility in lunar vehicles must be increased for Martian applications.

Table 6-16
BREAKDOWN OF GROSS WEIGHT

| Gross Weight, lb | Payload % | Mobility, % |
|---|---|---|
| 85.1 | 69.0 | 31.0 |
| 2,000 | 70.5 | 29.5 |
| 7,166 | 82.7 | 17.3 |
| 24,000 | 65.4 | 34.6 |
| Average | 71.9 | 28.1 |

Table 6-17 shows the performance characteristics of the three vehicles which have been thoroughly analyzed. Those performance characteristics which are primarily dependent upon geometry are plotted in Figure 6-27. The step and crevice performance is affected by the placement of payload components, both from the standpoint of geometrical interference and from the standpoint of uniform load distribution among the wheels. In Figure 6-27, minimum turning radius has been inverted and plotted as

Table 6-17
PERFORMANCE CHARACTERISTICS OF VEHICLES

| Vehicle Description | O/A Length (in.) | Gross Weight (lb) | Obstacles (in.) | | Maneuverability (in.) | | Gradeability* (DP/W) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Step | Crevice | Min. Turn. | Off Track | $k_\phi$=.05 to .08 | .5 | 3.0 | 6.0 |
| SLRV Phase I | 72 | 85.1 | 30 | 20 | 68 | 6 | .167 | — | — | — |
| Specified LSSM | 160 | 2,000 | 45 | 49 | 227 | 9 | .166 | .53 | .56 | .58 |
| MOLAB | 242 | 7,166 | 76.5 | 76.5 | 282 | 14 | .193 | .537 | .568 | .585 |

* DP/W in terms of lunar weight

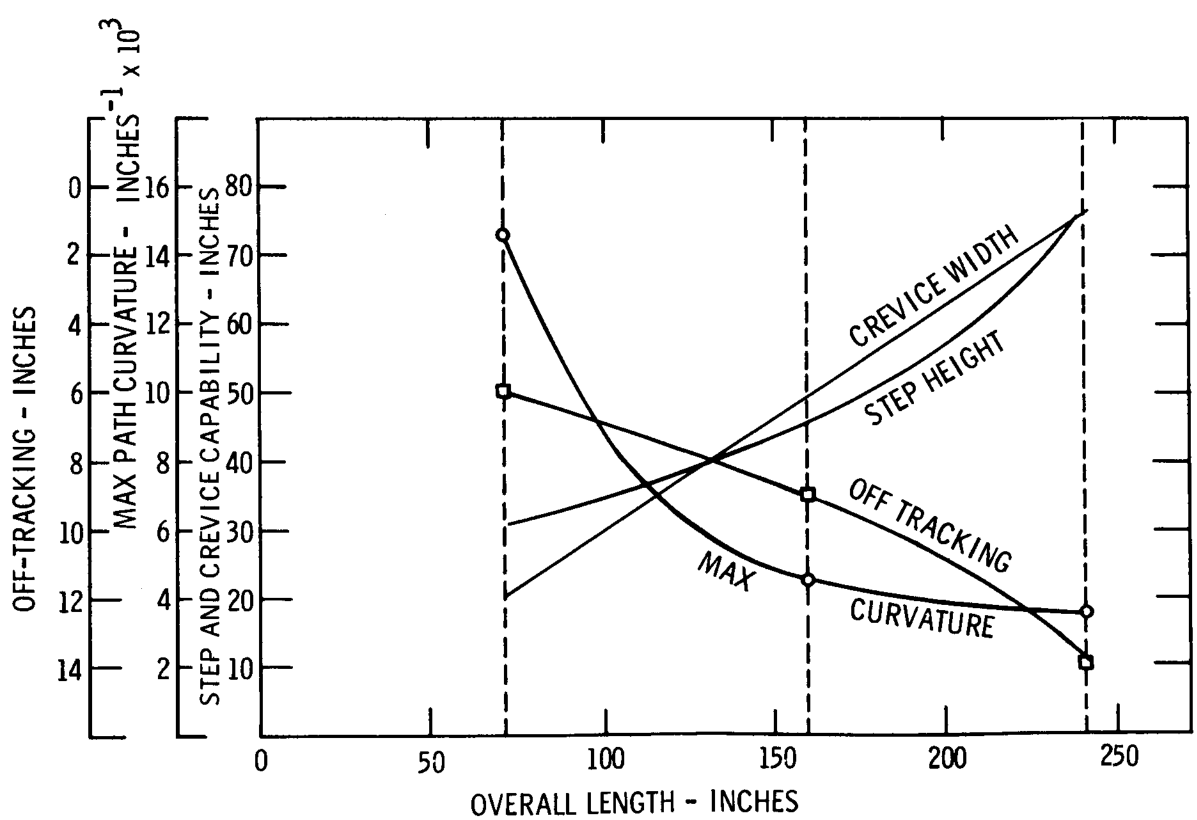



Figure 6-27 Obstacle Capability and Maneuverability

maximum curvature (1/R) and off-tracking has been plotted on a reversed scale. This is done to emphasize the desirability of making the maneuverability parameters small and to illustrate the inherent tradeoff between obstacle capability and maneuverability.

To a first approximation, obstacle capability is proportional to size and maximum path curvature is inversely proportional to size. Off-tracking depends on both size and steering geometry. Since the three vehicles used in the plot of Figure 6-27 have different steering geometries, the curve for off-tracking should be used merely as a rough guide.

Gradeability is expressed in terms of the ratio of drawbar-pull to weight, where the weight in this case is the gross weight of the vehicle on the moon. This is the sine of the angle of grade negotiable by the vehicle, and is primarily dependent upon the soil properties. Soil values used for the three vehicles were not the same in all cases. The SLRV calculations are based on a JPL soil model having the properties $k\phi = 0.083$, $\phi = 20^{\circ}$, and $n = 1.0$. The corresponding MOLAB value is based on the same model, but the LSSM value is based on a soil having $k\phi = 0.05$, resulting in a slightly lower relative value for DP/W. Allowing for this slightly lower value, the relationship appears roughly linear, but is at any rate largely independent of gross weight. There is, however, an apparent strong dependence upon soil properties.

The calculation of locomotion energy requirements has generally been based on the Bekker equations[22] used with a specified soil-slope model, supplemented by assumptions of the person making the calculations. Since the three vehicles considered have been evaluated with respect to vastly different assumptions and terrain models, no good comparison can be made. It can be shown, however, that locomotion energy for a given terrain and a specified set of assumptions is roughly proportional to the weight in situ. For the LSSM, having a lunar weight of 2000/6 = 333 lb, the energy required for level terrain having $k\phi = 0.5$ is about 120 watt-hr/km. Grade requirements for a given terrain model add to this. One is led, then, to this approximate relationship for moderate soils:

$$E = 0.36\ w + \text{Grade energy}$$

where $E$ is energy in watt-hr/km, and $w$ is weight in pounds in situ. For harder soils energy will be less and for softer soils it will be greater.

Most of the data given above are based on vehicles designed for the lunar environment. Since the Martian gravity is about 2-1/4 times that of the moon, certain weight-dependent values will be different for Mars. A cursory study of this effect indicates, for example, that mobility elements of Martian vehicles will constitute about 40 percent of the gross weight rather than the 30 percent cited above for lunar vehicles.

Drawbar-pull-to-weight ratio will remain about the same, but locomotion energy for a vehicle of comparable size and earth weight will increase by a factor of about 2-1/4. This will require either an increase in power and less weight available for science, control, and communication, or a decrease in speed, or both.

### 6.4.2 Unconventional Vehicles

A wide variety of vehicles have been conceived for use in extraterrestrial surface exploration. These include machines which fly, walk, jump, crawl, and slide. Many trade-off analyses have been conducted by numerous agencies and companies, and, except for quite special applications, the results have usually shown that the more conventional wheeled or tracked vehicles are best. Of these, the vast majority seem to employ wheels. On the basis of its own analysis, AC-DRL has concluded that wheels are generally preferred to tracks for the applications considered. The present survey thus deals only with wheeled vehicles.

The variety of wheeled vehicles encountered in the survey covered the range from one wheel (a sphere) to ten or more. Most of these were simple concepts and the design and performance data associated with them are, at best, "engineering guesses." The most credible data are those which resulted from a preliminary design effort.

However, in addition to mobility considerations it is important to consider the facility with which a vehicle may be controlled remotely. This is particularly true in fly-by-wire modes.

Experimental remote control work by Adams at Stanford[(3)] showed a vehicle with wheels mounted for crabbing capability was exceptionally easy to maneuver around obstacles. This vehicle was only a test bed for vehicle control experiments. To find out whether or not such a steering mode would compromise mobility and other engineering considerations would require an extensive design study, and one would also have to consider the added complexity that this capability might introduce.

## 6.5 TELECOMMUNICATIONS

The important telecommunications parameters relating to the analysis of an RV system are:

1. The number of bits per second which can be handled each way through the data link.
2. The signal-to-noise ratio between the vehicle and the output of the data link in the down direction. In the up-link the signal-to-noise ratio between the command encoder and vehicle is important.
3. Round-trip signal time.

Fundamentally, the ability of a deep-space communication system to track, command, or acquire telemetered data from a vehicle is a function of the ratio of signal level to noise level. Signal level varies inversely with the square of the distance of transmission. Design of a system to communicate out to a particular distance takes the form of making up for space losses by transmitter power, antenna gains, and receiver sensitivity. Minimizing noise levels depends on many factors, including avoidance of RF noise sources and design of the receiver preamplifier.

Reference 31 forecasts Moon-to-Earth data rates ranging from $10^6$ bits per second to more than $10^7$ bits per second before 1970. This is for a 10-watt transmitter and 26dB antenna on the moon. To transmit one 500-line image per second with 64 grey levels, $1.5 \times 10^6$ bits per second is required.

The Mars-Earth communication link presents a problem that is much more difficult than the Moon-Earth communication link because distance is three orders of magnitude greater and rotation rate relative to the earth sphere is two orders of magnitude greater. Rover antenna gains will be limited by vehicle dimensions and mobility characteristics. In addition, it may be difficult to achieve precise tracking because of limitations on the antenna drive mechanism size, weight, and complexity. Writers on the subject of the Mars-Earth communication link have used so many diverse assumptions that it is difficult to correlate these and to arrive at a conclusive estimate of feasible data rates for a roving vehicle. However, from informal discussions with JPL personnel who have conducted preliminary studies of data rates from Mars for various antenna sizes, it appears that the bit rate from Mars will be two to four orders of magnitude lower than the bit rate from the moon.

This is further borne out by the results of studies performed on the Voyager Capsule mission by TRW Systems Group.(7) Extrapolating from the values published by TRW Systems to power levels and antenna gains likely to be of interest on roving vehicles, the relationships shown in Figure 6-28 are reached. While these may be somewhat sensitive to specific assumptions, they are used in this study as a basis for related analyses.

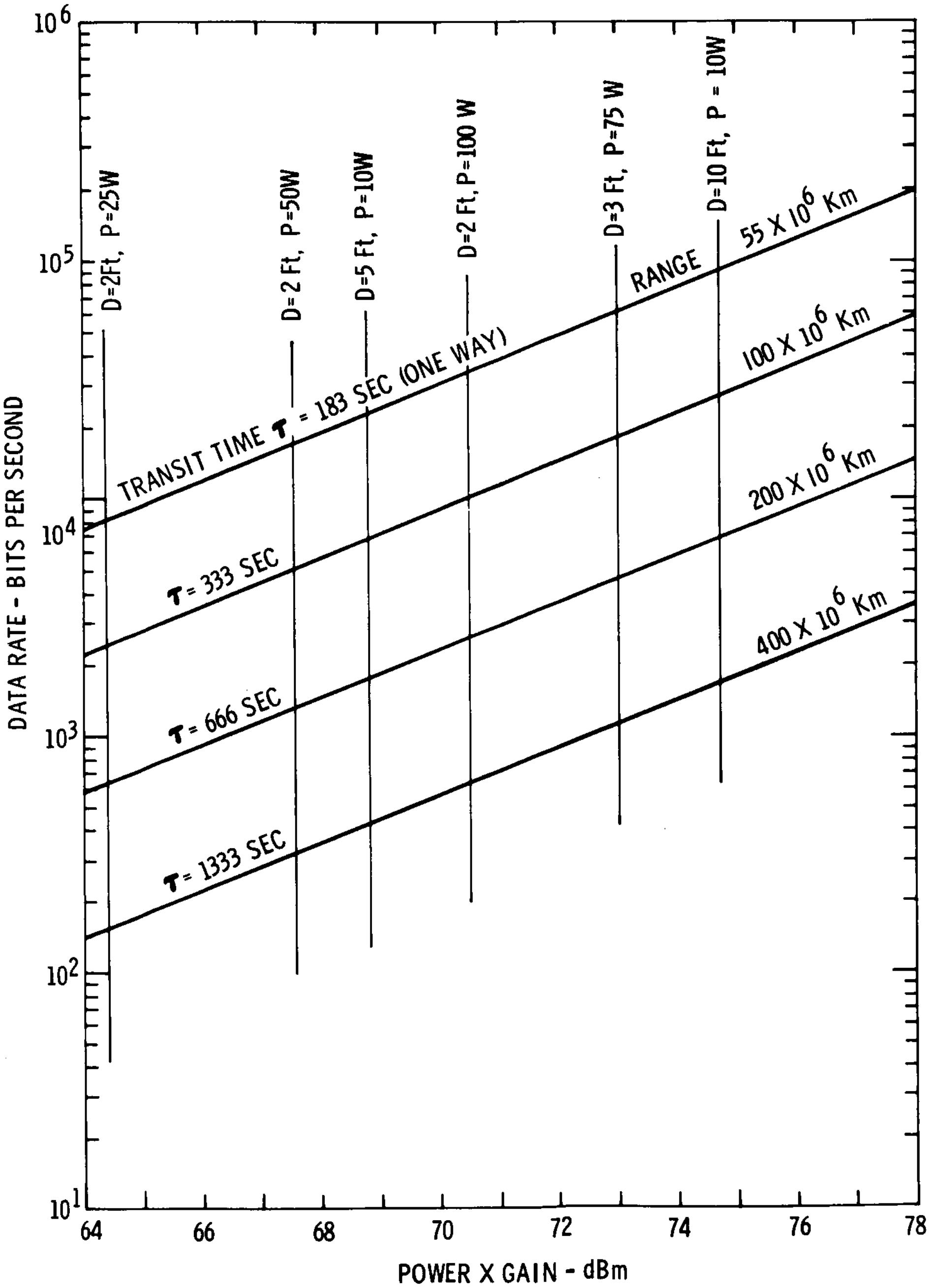



Figure 6-28 Mars-Earth Information Rates

## 6.6 POWER

To some extent the choice of approaches to RVMC may depend upon weight trade-offs reflected in the power and energy requirements. It is therefore appropriate to include a brief summary of some of the applicable data.

An electric power source is required by the RV for

- Propulsion and steering motors
- Sensors and associated equipment
- Data Processing and control equipment
- Telecommunication equipment
- Thermal control heaters
- Scientific instruments.

The atmospheres of the moon and Mars limit the possible choices of power sources to nuclear-reactor, radioisotope, solar-panel, fuel-cell, and battery systems. The relatively low power requirements of the vehicles to be considered in this study eliminate any consideration of reactor power systems. The desire to define a roving vehicle which is not range-limited, and with operating lifetimes of from months to years, tends to eliminate fuel cells from practical consideration. Likely candidate power systems are:

(1) radioisotope-thermoelectric generator + high energy density (15–20 watt-hours/pound) batteries.
(2) solar panels + low energy density (2–3 watt-hours/pound) batteries.

The nickel-cadmium cell is the only proven reliable battery for long-term service where rapid recharge is needed. For the Martian case, this battery would probably be used whenever a solar-panel power system is used, because of its ability to survive deep discharges. If an operating life of several years is necessary, an energy density of 2 watt-hours per pound can be assumed for the nickel-cadmium cell.[32]

The silver-zinc battery has a relatively short cycle life but, for the lunar case, studies might indicate the existence of workable silver-zinc/solar-panel combinations.

A radioisotope-thermoelectric generator (RTG) power system operates continuously and requires batteries to supply only peaking power. Therefore, the silver-zinc cell can be considered appropriate for this power source and can produce 15 to 25 watt-hours per pound, depending upon the depth of discharge.

At present, RTG's produce about 1.2 watts per pound. A capability of three watts per pound within the next five years has been predicted.[33] For cooling purposes, a 2 steradian field of view is required for thermoelectric generators. An RTG produces nuclear radiation and magnetic fields which may interact with other rover subsystems. These fields can lead to the compromise of some of the scientific experiments or can cause radiation damage of electronic components during a long-duration mission.

Solar-cell power systems are being used on 30 or 40 different spacecraft; the range of power outputs is from 15 to 500 watts. Conclusions reached by RCA[11] in designing an energy source for the Surveyor Lunar Roving Vehicle are as follows:

- RTG's are competitive with orientable solar arrays in the approximate range of 1.5 to 2.0 watts per pound of converted power for operating times greater than six to ten hours.
- The orientable solar array has limited growth capability compared to an RTG. Power per unit weight depends on distance from the sun. It is about 2 watts per pound for earth orbit.

In addition, solar panels may suffer performance degradation from meteorite damage and dust or from atmospheric conditions, and they require mechanisms for orientation. Their area may present structural problems in the high winds that may exist on Mars. It would appear that, if present predictions of RTG performance are realized, this would be the preferred approach to powering unmanned roving vehicles on Mars, and probably also lunar vehicles.

# 7.0 BALANCE BETWEEN ON-BOARD EQUIPMENT AND GROUND SUPPORT EQUIPMENT

In this section the differences in the balance between on-board and ground support equipment as required for the fly-by-wire mode and for automatic modes are discussed. The major differences are in vehicle sensor requirements, demands on the communication link, and in the data processing, data storage, logic, and procedures, both on the vehicle and on earth. In an actual design there would also undoubtedly be minor differences in the vehicle mobility and power subsystems for fly-by-wire and automatic configurations.

Ground based equipment requirements are similar for the two cases. The difference lies in the intermittent and/or monitoring nature of ground control for semiautomatic and automatic operation. Thus for efficient fly-by-wire control on the moon greater equipment accuracy and speed of processing for terrain assessment is required than for automatic modes where the burden of accurate terrain assessment lies with on-board equipment. In the first case high quality images whose geometry is accurately known may have to be positioned rapidly and precisely for photogrammetric analysis. This would probably require special, high quality plotting equipment. In the second case conventional plotters could be used in a more leisurely fashion without delaying vehicle progress.

Likewise, less rigorous requirements apply to much of the other ground equipment required for vehicle control when the system is used in an automatic mode. On the other hand greater care would have to be taken in developing strategy to avoid placing too great a reliance on vehicle capability for keeping out of trouble.

Table 7-1 lists space-based equipment requirements and their applicability for fly-by-wire or automatic modes.

As shown in the table, the sensor functions required for normal mode operation in either fly-by-wire or automatic modes are the same. The primary difference will be in the long-range terrain sensor implementation. Stereo images suitable for terrain assessment by a human being on earth are not suitable for terrain assessment by a

Table 7-1
SPACE-BASED EQUIPMENT FOR TYPICAL RV OPERATIONS

| | Fly-By-Wire | | Semi-Automatic | |
|---|---|---|---|---|
| | Normal Mode | Intermittent | Normal Mode | Intermittent |
| **Mobility** | | | | |
| Mobility Subsystem | x | | x | |
| Drive Control | x | | x | |
| Steering Control | x | | x | |
| **Sensor Subsystem** | | | | |
| Vehicle Engineering Sensors | x | | x | |
| Short Range Terrain Sensors | x | | x | |
| Long Range Terrain Sensors | x | | x | |
| Environmental Sensors | x | | x | |
| Navigation Sensors | x | | x | |
| Science Sensors | | x | | x |
| Long Range Sensor Drive | x | | x | |
| Long Range Sensor Drive Control | x | | x | |
| Long Range Sensor Parameter Control | x | | x | |
| **Logic** | | | | |
| Master Control Logic | – | – | x | |
| Central Decoder and Verifier | x | | | x |
| Fly-by-wire Command Sequence Storage | x | | | x |
| Emergency Command Generator | | x | | x |
| Navigation Computer | x | | x | |
| Out-of-tolerance Detector | x | | x | |
| Thermal Control Logic | x | | x | |
| **Telecommunications** | | | | |
| Sensor Data Storage | – | – | x | |
| Data Compressor | – | – | x | |
| Data Conditioner & Multiplex | x | | | x |
| Diplexer | x | | | x |
| Transmitter | x | | | x |
| Omni Antenna | x | | | x |
| Omni Receiver | x | | | x |
| Directional Antenna & Drive | x | | | x |
| Directional Antenna Drive Control | x | | | x |
| **Power Subsystem** | x | | x | |
| **Thermal Control Subsystem** | x | | x | |

machine, as discussed in Section 6. Whether automatic terrain assessment equipment will entail more or less equipment complexity on the vehicle will depend on future invention and development.

Under logic equipment the master control logic is only required for automatic modes. Its main function will be to combine terrain assessment data, dead reckoning vector summations from the navigational computer and the required vector to the goal to produce steering and motion commands.

The command sequence storage and central decoder, used routinely in fly-by-wire modes are only used for standby in automatic modes.

As shown in the table, the communication equipment used for routine control in fly-by-wire modes will mainly be used intermittently for monitoring or for receipt of instructions in the automatic modes.

Sensor data storage and data compression are less likely to be used in fly-by-wire than for automatic modes since their cost in weight and complexity must be traded against the requirements for mission speed.

In general, any system which operates in an automatic mode will have a requirement for fly-by-wire alternative or back-up operation. The degree to which this back-up mode meets all of the requirements applicable to a primary fly-by-wire system will depend upon cost trade-offs and the likelihood of a need for the mode. A semiautomatic system is not merely one where the human, ground-based functions are transferred to the vehicle, but will ordinarily involve a radically different approach to sensing and decision making. Provision of fly-by-wire back-up capability may then also affect the on-board equipment as well.

# 8.0 HUMAN ENGINEERING ASPECTS

## 8.1 HUMAN FACTORS

In any control situation, no matter what the degree of automation, an interface ultimately exists between the personnel involved and the hardware subsystems which are required to respond to human control. The human involvement can be considered as a personnel subsystem comprising people and their functions. The interface between this subsystem and the hardware may then be defined in terms of the tasks which humans are required to perform in overall system operation.

The basic unit of appraisal of personnel subsystem activity used here is the task analysis. A task will be defined as a limited and orderly grouping of individual human activities directed toward the accomplishment of a desired system state change. Human functions are comprised of one or more tasks.

There is at present no adequate systematized methodology for assigning functions to man or to machine. The allotment must be made by a consideration of each individual function as it relates to the total system. The basis for this allotment is the weighing of human capabilities against machine considerations for system effectiveness. Human-related system effectiveness is dependent upon both primary human factors and certain secondary human operating parameters.

The primary human factors are those associated exclusively with human performance. Fundamentally, man perceives, judges, and acts. These operations are carried out under wide ranges of physical and psychological states of the organism. When such states influence the performance of a task, a fourth factor – stress – is added.

Secondary factors are those parameters which are associated with any system component, only as they apply, however, to the human. Thus error rate, time to complete, information storage capacity, and training (essentially a change in component design!) etc., come under this heading.

## 8.2 FUNCTIONS OF HUMAN OPERATORS

The level of detail that can be attained in task analysis is dependent upon the detail in which system configuration is available. Without knowing what hardware is involved it is not possible to be completely specific with respect to the skills, knowledge, perceptions, judgements, and motor abilities required to accomplish a given function.

It is possible, however, to develop a methodology which will allow estimates of the upper limits likely to be placed upon human performance no matter what level of design is being considered. Such a methodology is discussed below.

System functioning proceeds as an integrated group of operations. These operations may be carried out contiguously in series, or concomitantly in parallel. Or they may take place in combinations of the above (series-parallel). Such functioning may be shown graphically by an operational flow diagram. From the diagram, a few of the operations may be assigned immediately to man or to machine. Most of them, at this level, must be carried out conjointly.

The purpose of this section is to describe the fly-by-wire and semiautomatic configurations by general flow diagrams and, where possible, to characterize them by the degree to which both primary and secondary human factors are involved. Every major operation will be assigned coded numbers representing the greatest extent to which each of the following factors is involved in that operation:

- skill levels required
- human stress level associated with the operation.

In addition, operations will be assessed for:

- degree of training required
- estimated time to complete.

When a subgroup of simultaneously initiated operations is conducted in parallel, the operation having the highest value for a given parameter becomes the pacing function for that subgroup. It is therefore possible to assemble a single-thread function flow which maximizes the involvement of any given parameter. For example, an important consideration for any operational complex may be that of time-to-complete. A time line for single-thread operation can be constructed by choosing as in-line functions those successive ones which require the longest time to complete. From this time line, an analysis may be made to determine what human tasks overlap in time. Operator loading studies may be made, and man/machine assignments refined to optimize personnel subsystem performance by taking into account required system reaction times, human fatigue factors, duty cycles, etc.

Individual operations which occur in parallel, although they do not contribute to overall system operating time, may of course be similarly examined.

The time lines for the fly-by-wire and semiautomatic configurations are shown in Figures 8-1 and 8-2, respectively. The fully automatic configuration need only be considered at the interfaces where the human enters and leaves the operational sequence.

Certain preparatory functions are common to all modes, though the nature of their implementation may differ somewhat. For this reason, the first fourteen blocks represented in the semiautomatic mission (Figure 8-2) are considered to be the same at this level as those for the fly-by-wire mission shown in Figure 8-1.

The operational flow diagrams of Figures 8-1 and 8-2 provide a matrix for system evaluation with respect to the remaining factors on the above list. At the functional level represented, only a very general idea of their system impact may be gained. The methodology, however, is applicable to systems described in ultimate detail, and for that reason is presented here.

Each operation consists of a task or a number of tasks. The task element having the most stringent requirements with respect to a given factor is used to characterize each task; the most demanding task, in turn, is used to characterize the operation in which it lies.

The above procedure is accomplished by a system of coded descriptions, as indicated below. Operations are then assigned appropriate code numbers.

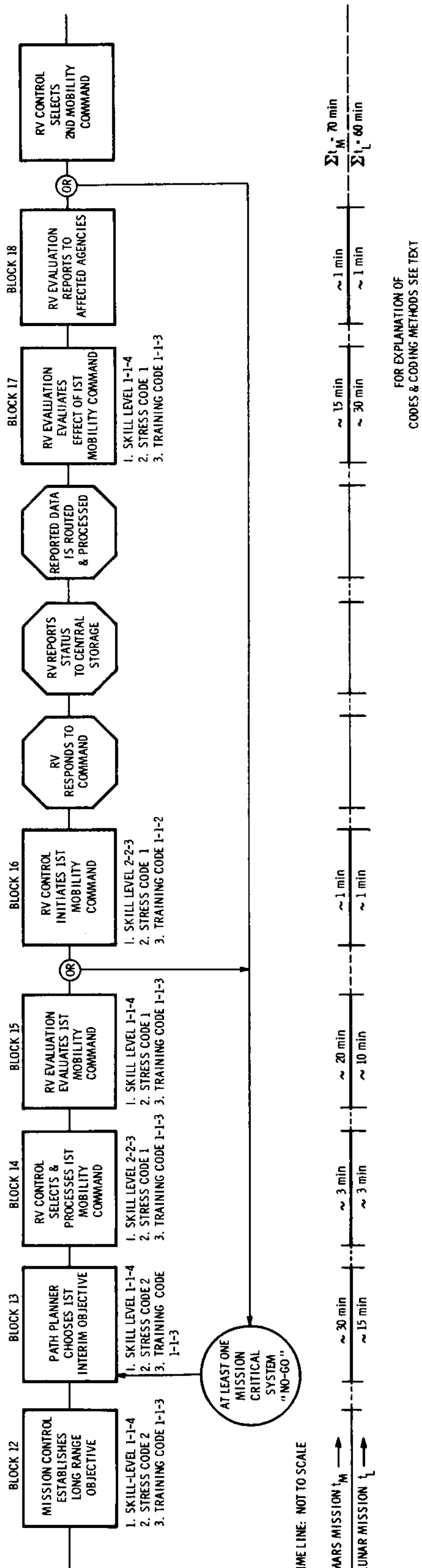



Figure 8-1 Single-Thread Operational Flow, Fly-By-Wire Configuration

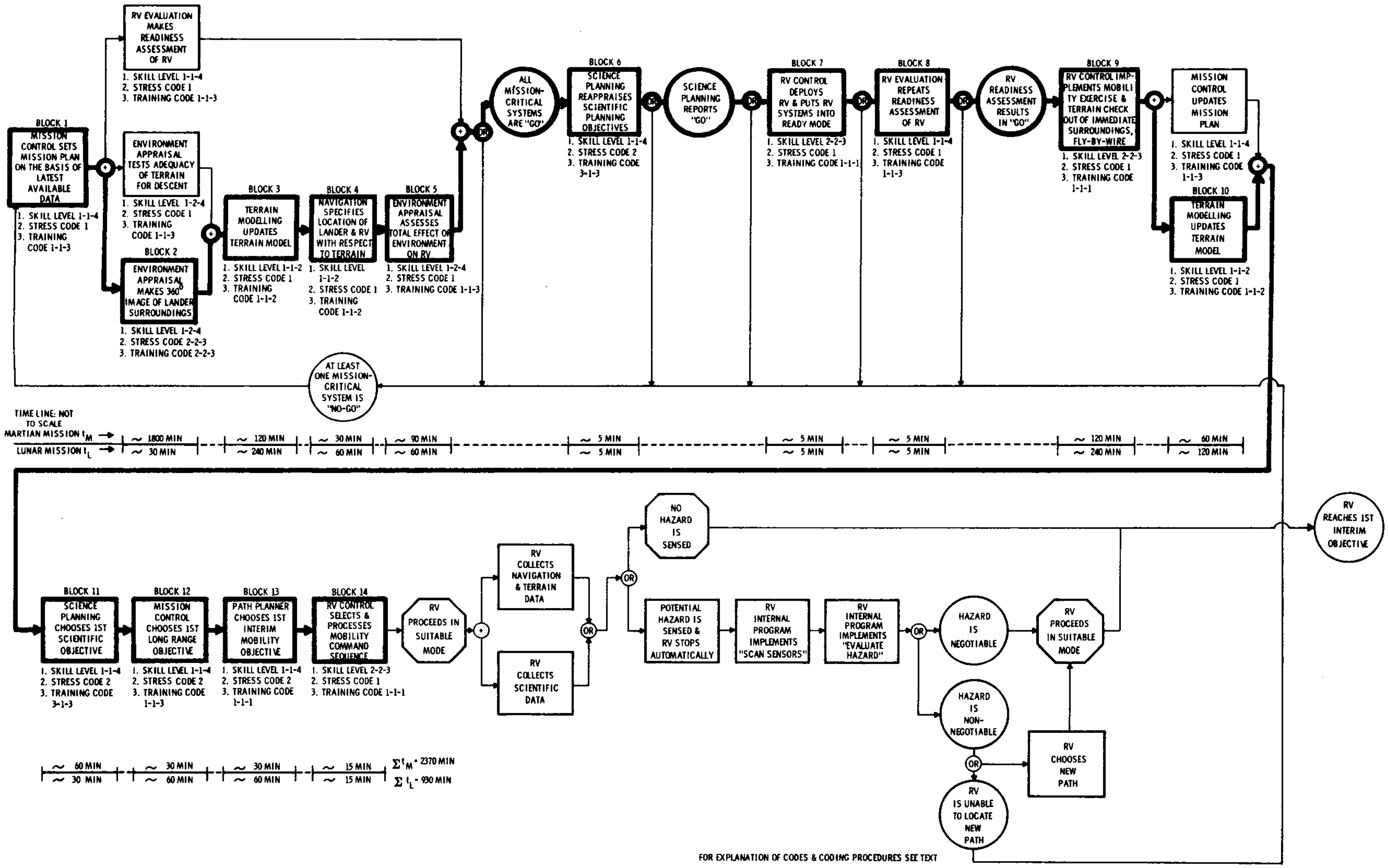



Figure 8-2 Single-Thread Operational Flow, Semiautomatic Configuration

### 8.2.1 Human Skill Levels Demanded

Human skills are considered as containing the elements of perception, judgement and motor action

(a) Perceptual

| Code | Description of Task Nature |
|---|---|
| 1 | Difficult perception of obscure but meaningful relationships; ability achieved only after intense training and experience and maintained only through constant practice |
| 2 | Moderately difficult perception of routine relationships; ability achieved after limited training and practice and readily retained |
| 3 | Perception of relationships obvious after simple familiarization or minimum instruction |
| 4 | Perception of Go/No-Go conditions, out of tolerance conditions, from simple indicators. No training involved. |

(b) Judgmental

| Code | Description of Task Nature |
|---|---|
| 1 | Decision requires special knowledge, intense training and continuous practice in problem solving |
| 2 | Decision requires practical knowledge, moderate training, but a minimum of practice in problem solving |
| 3 | Decision requires only average knowledge and familiarization with problem |
| 4 | Decision requires only yes-no determination of extremely simple problem; no familiarization needed |

(c) Motor

| Code | Description of Task Nature |
|---|---|
| 1 | Highly coordinated and precisely timed movements learned only after intense training and retained only by constant practice |
| 2 | Coordinated muscular dexterity, learnable through moderate training. Skill will not be lost through fairly long periods of disuse |
| 3 | Nonprecise muscular activity, learnable through simple demonstration and retained indefinitely |
| 4 | Low-level muscular activity; part of normal person's repertoire without demonstration or training |

The task element requiring the highest possible skill level is accordingly assigned the coding 1-1-1: the lowest possible level is given by the code 4-4-4. The operations are assigned the coding of the highest skill levels represented by any task they contain.

In Figures 8-1 and 8-2 the skill codes are entered immediately below their related function blocks as Item 1.

### 8.2.2 Human Stress Levels Involved

Stress enters human performance in two ways. One is related to the emotional content of the situation, the other to the psycho-physiological (fatigue, oxygen deprivation, etc.) content.

Under the assumption that mission success is the prime objective of the personnel concerned, emotional stress level for a task is assessed by considering the effect on system operation of failure of the individual to accomplish the task successfully. Psycho-physiological stress will be considered later under a separate heading. Emotional stress coding is accomplished as follows.

| Code | Failure to do task properly results in: |
|---|---|
| 1 | Mission abort |
| 2 | Loss of important scientific data |
| 3 | Loss of important mobility data |
| 4 | Major equipment damage |
| 5 | Major mission delay |
| 6 | Minor mission delay. |

In Figures 8-1 and 8-2 the emotional stress level assigned is indicated as Item 2 below each functional block.

### 8.2.3 Human Training Requirements

Training requirements are set on the basis of the knowledge, skills, attitudes, and methodologies the human must deal with in the proper execution of his task. Since training is used to improve skills, it may reasonably also be broken down into perception, judgment, and motor. An individual is not trained in any one of these categories in complete disregard of the remaining ones. It seems best, therefore, to classify training requirements by the degree of sophistication required of the training media in order to establish the required abilities. This is done as follows:

| Code | Training Media Recommended |
|---|---|
| 1 | Training and system simulation devices, and 2, 3 and 4 below. Continuous updating of skills. |
| 2 | On the job training (OJT) and 3 and 4 below |
| 3 | Audio-visual media and 4 below |
| 4 | Verbal media only (lectures, instructions, etc.) |

In Figures 8-1 and 8-2 the training requirements are entered as Item 3 below the appropriate function blocks.

### 8.2.4 Fully Automatic Mode

In the fully automatic system the operations are essentially the same as those for the semiautomatic for the first fourteen blocks of Figure 8-2. The choice of a long-range objective would be followed by procedures for entering the automatic mode, and the RV would "take over" from that point on. The tasks associated with these 14 functions would differ somewhat for the two systems because a different level of detail of information is required, and decisions are based upon predictions made farther ahead in space and time in the fully automated case.

When the tasks for these functions are specified in detail, they will reflect differences in human factors weightings, with correspondingly different code assignments for the semiautomatic and fully automatic configurations. At the very general level of Figure 8-2 differentiation should probably not be made.

## 8.3 PERSONNEL SELECTION, TRAINING AND TESTING

The development of qualified personnel to operate and control an RV is an integral part of the system development sequence. This effort should consist of the following phases:

(a) Analyzing the major function blocks to determine the individual roles required to accomplish each function

(b) Assessing the requirements of each role and deciding what selection, training and evaluation procedures will be most effective in meeting these requirements

(c) Selecting and assembling qualified personnel capable of performing the major functions into subgroups

(d) Integrating the performances of each of these groups into an overall system operational structure

(e) Evaluating individual, group, and total system performance against acceptable performance criteria.

The fly-by-wire and semiautomatic configurations do not differ essentially in the identities of the functions which must be accomplished; rather, the differences lie in the way in which they are carried out. Table 8-1 lists these functions and the gross human parameters which must be associated with each. Where the RVMC function is part of a larger system function (as for example, Science Planning and Evaluation), only those parameters associated with the RVMC are considered. Thus, as the latter columns of the table indicate, one group member of Science Planning and Evaluation trained specifically in the constraints and requirements imposed by RV mobility should be immediately available during RV operation.

There are differences in execution times even though the same functions will have to be performed, either explicitly or implicitly, in the fly-by-wire and semiautomatic configurations. In general, decisions which involve a sequence of actions will take longer than those concerned with single responses only. Some functions in the semiautomatic mode will take longer than their fly-by-wire counterparts for this reason.

On the other hand, decisions which are automated will in general require less time than those dependent upon human response times; for this reason, some functions in the semiautomatic mode will be accomplished in less time than their counterparts in the fly-by-wire configuration.

The amount of available information also affects decision time. What may seem relatively simple decisions in the case of lunar missions, for example, may actually be allotted much more time than in the corresponding Martian configuration, simply because, with more data available, greater efforts may give greater returns, and greater skills are required.

The allotted times for Figures 8-1 and 8-2 are therefore somewhat different. The times assigned to the different functions are, to say the least, quite approximate. Until system simulation has been achieved, and the complexities of the various operations assessed in greater detail, the values must remain the crudest of estimates. Nevertheless,

Table 8-1

GENERAL TASK ANALYSIS FOR FLY-BY-WIRE AND SEMIAUTOMATIC RVMC SYSTEM CONFIGURATIONS

| Function | Human Abilities and Knowledge Required | Skill Level Coding, Maximum | | | Training Requirements Coding, Maximum | | | Emotional Stress Coding, Maximum | Required No. of RV Personnel Available During System Operation | | | | | | Maximum Recommended Continuous Duty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Lunar Mission | | | Mars Mission | | | |
| | | Percep-tual | Judge-mental | Motor | Percep-tual | Judge-mental | Motor | | FBW | S/A | F/A | FBW | S/A | F/A | |
| Science Planning & Evaluation | Scientific expertise and the ability to plan on the basis of meaningful relationships between scientific objectives and mobility constraints | 1 | 1 | 4 | 3 | 1 | 3 | 2 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 10 hours |
| Mission Control | Overall Systems integrating ability, understanding of all phases of RVMC system, ability to maximize system effectiveness in achieving both scientific and mobility objectives | 1 | 1 | 4 | 1 | 1 | 3 | 1 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 6 Hours |
| RV Evaluation | Understanding of RV eng. parameters, mobility parameters and terrain effects on RV mobility and data collecting functions | 1 | 1 | 4 | 1 | 1 | 3 | 1 | 2 | 2 | 1/2 | 2 | 2 | 1/2 | 6 Hours |
| Navigation | Understanding of terrain-RV mobility relationships, position determining techniques, RV mobility parameters | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 6 Hours |
| Terrain Modelling | Depends on the model of choice; may require skills in photometry, photo interpretation, computer software technology, non-visual image interpretation, mapping technology | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 3 | 3 | 1-1/2 | 3 | 3 | 1-1/2 | 6 Hours |
| Path Planning | Understanding of RV macro-mobility parameters, vehicle-terrain interaction, RV logistics | 1 | 1 | 4 | 1 | 1 | 1 | 2 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 6 Hours |
| RV Control | Understanding of RV micro-mobility parameters, immediate vehicle-terrain relationships, knowledge of vehicle critical states, knowledge of command procedures | 2 | 2 | 3 | 1 | 1 | 2 | 1 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 4 Hours |
| Environment Appraisal | Understanding of environmental survey techniques within RV repertoire and of data processing methodology required to make data meaningful to terrain modeller | 1 | 2 | 4 | 1 | 1 | 3 | 1 | 1 | 1 | 1/2 | 1 | 1 | 1/2 | 6 Hours |
| | | | | | | | | TOTALS | 11 | 11 | 5 | 11 | 11 | 5 | |

as system design progresses and the operational flow diagrams are supplemented by operational sequence diagrams (OSD's) delineating each human performance in detail, times will be specifiable more and more accurately.

The time line data from Figures 8-1 and 8-2 may be examined in various ways. Before even rough estimates of overall mission times can be made, the missing links in the time-lines must be filled. These arise because of data processing, communication and mechanical delays which are not fundamentally due to human factors, but necessarily contribute to the total picture.

The operation flow diagrams and their associated time lines and factor coding, even at the levels presented can then be used to draw certain conclusions with respect to system operation. Among these, the following items are worthy of note.

1. Total mission times required, as presently conceived, may be a limiting factor in system effectiveness. Since human evaluations and decisions contribute a significant portion to these times,
   (a) Definitive procedures and methodology should be developed so that adequate solutions to human judgement problems may be reached in minimum times.
   (b) Every human function which can be carried out on the outside of RV operating-window constraints should be so scheduled, since human errors and processing times are difficult to predict and may introduce untenable system delays. This is particularly true of operations involving high perceptual and judgmental skill levels.
   (c) It is the nature of the systems involved that where operating windows are shortest it also takes the longest to make equivalent assessments. Such assessments should therefore be made by machine modes rather than human modes, wherever possible.

2. System operation appears to be feasible in a manner such that stresses other than emotion will not be involved unless adequate personnel are not available to maintain an acceptable work schedule. Fatigue, for example, will not become a factor unless shift times must exceed the general limits recommended in Table 8-1 and routine 'breaks' cannot be provided.

3. Functions with high associated skill levels must be simulated realistically for training purposes. Emphasis should be placed upon performance as it is integrated into overall team operation, and upon the simulation of error-free data processing.

   (a) Under high stress levels
   (b) Under rigid time constraints
   (c) Under conditions conducive to low levels of alertness (boredom, etc.).

4. Control of an RV in operation will require highly coordinated information exchange and processing. It is recommended that special study be given to communication and decision channels in the form of link analyses, etc., aimed directly at the remote control problem.

5. RV operation as envisioned in this study will be carried out in a step-by-step manner whenever humans are involved. Therefore time lags which cause operator cues and control movements to be out of phase with RV responses will not be a major source of difficulty.

Personnel selection, training and testing do not proceed independently. In a system without the precedent of an operating history, tentative operator selection must be made on the basis of past performance of the individuals concerned. The assessment should be made under conditions as nearly paralleling system operation as possible. When the individual tasks have been specified it is always possible to devise predictive tests which will help in the selection of people for the various roles. However, since the total number of people required in the RVMC system is small, the efforts required in developing test batteries would be greater than the returns would warrant. Also, because the successful performance of individual tasks is no guarantee of success as a team member, training and testing functions should be accomplished by simulating system operation as faithfully as possible and evaluating each individual's performance against the criterion of system effectiveness.

The role of simulation can hardly be stressed too much. Once the hardware is defined and tentative role assignments made, team training should be undertaken in exercises that

- place realistic demands upon both human and machine system effectiveness, and realistically simulate system operation (actual RVMC controls and displays must be used wherever possible)

- train the personnel subsystem in coordinated team effort so that vehicle motion constraints are imposed upon overall system operation, and the team responds as a unit
- allow for increasing proficiency by progressively matching the difficulty of the motion control problems to the ability of the team.

The effects of personnel selection, training and testing upon performance under emotional stress require special note. The stress demands imposed by RVMC may be quite high, as indicated in the task analysis tabulation. System degradation may be minimized by taking into account the following factors.

(a) Individual differences in ability to operate under emotional stress are quite large. People who perform well initially under stress improve with training and tend to retain such improvement. People whose performance is marginal to start with may show marked improvement, but when stress limits are exceeded return to a lower level of performance than the good performers.

(b) Simulation training should be carried out until both individual and team performances reach a plateau considerably above actual system operational demands. RVMC involves tasks where the penalties for error are severe; also, the operational stress demands will in general be greater than the simulated system's demands. Therefore RVMC training tasks should be <u>overlearned</u> to minimize the possibilities of operational error.

(c) Training may – and should – include performances up to stress level 4 (major equipment damage). In general this is accomplished by keeping the operators in ignorance of safeguards incorporated into the simulation system.

(d) Where the best available human performance is marginal for system success, backup systems must be provided, as well as safeguards against performance error.

## 8.4 DUTY CYCLES AND FATIGUE

Obviously, the individual tasks associated with the functions listed in Table 8-1 will vary from high-level decision making to simple watch-keeping. The constraints imposed by restricted communications windows, low data rates from overseas DSIF stations and possible time-sharing between RVMC data and other traffic information, may limit operational periods for the fly-by-wire and semiautomatic systems to a maximum of something less than twelve hours.

Duty cycles may be adjusted accordingly. High motivational factors will be attendant with even routine missions. Those tasks which are carried out in response to an intermittent data flow, however, are not sensitive to performance degradation over periods as short as this unless the stress factor becomes too great. Any or all of the high-level tasks associated with each function (except Science Planning and Evaluation) can result in mission abort if improperly performed. Thus, the only way in which stress levels could conceivably exceed system capabilities would be for a large number of critical situations to arise at once or in succession. This might happen, for example, if it became necessary to operate the system in a degraded condition, or if the conditions encountered taxed the fully operational system to the utmost.

For all RVMC functions except the Science Planning and Evaluation component it will be necessary, therefore, to provide backup, either by provisions for added personnel or for cross training between members of the same group.

In Martian missions information flows will be of such nature that all of the system functions can be carried out without undue concern for fatigue or boredom effects, provided total shift times do not exceed the tabulated values. For lunar missions, particularly in the fly-by-wire mode, the RV control function may encounter error-producing situations because of heavy or continuous operator loadings. This duty cycle should be shortened as necessary.

The fully automatic system interfaces only briefly with that part of the personnel subsystem which must operate under time constraints. Duty cycles may therefore be assigned upon other considerations than fatigue or other performance degrading factors.

## 8.5 DATA AND DISPLAY REQUIREMENTS

For the purposes of the RV study, displays and controls may be divided into two classes:

(a) Those associated with already established operating procedures and data handling methodologies

(b) Those associated with methods and procedures not as yet firmly established in the state of the art.

The first group includes meters, gages, standard CRT displays, rotary selector switches, etc., as used in monitoring and controlling conventional system parameters.

Their successful integration into the system can be accomplished by conforming to standard human engineering practices in system design, and will not be discussed further here.

The second group involves new control and display techniques or new combinations of old techniques employed in the context of a remotely controlled RV. Control and display effectiveness must accordingly be established through simulation or operational use.

Particular attention must be given to terrain modeling displays which use predictive techniques and which in all likelihood will employ artificial cues to describe system states.

Similarly, the control function must be integrated into the display complex; it is possible that displays which present enhanced or diminished representations of control errors may be effective in RV motion control. Questions raised here are only answerable by realistic simulation and carefully designed experimental techniques.

Once an adequate technique for meeting display and control requirements is devised it can be incorporated into a data processing design which allots functions to specially configured personnel units, or work stations. These work stations will be provided with the specific needs of the functions they represent, but the concept of need must be interpreted rather broadly.

For instance, it is axiomatic that a given operator should have available in usable form all of the information he requires to accomplish his task, but no more. Excess information only increases the chances for error. Yet, in the highly motivated situations of space mission operation, knowledge of overall mission progress is a necessity. If operators do not have this information readily available they may leave their stations at critical times in search of it, particularly when theirs is a monitoring function where state changes do not occur frequently.

Obviously, data processing and display requirements must await system specification before the ultimate means of meeting these requirements is chosen. Decision, for a machine system component, is easily achieved through proper programming, although the repertoire may be limited. For the elements of the personnel subsystem, the decision function is a variable one, subject to human error and variations in performance level as the price of a large and versatile repertoire. The human decision element should thus receive maximum consideration in system design.

# 9.0 SYSTEM PERFORMANCE AND TRADE-OFF ANALYSIS

In order to gain some insight to the manner in which system parameters trade off, a preliminary quantitative analysis was made. The approach to this analysis was to assume a fly-by-wire system using stereo imaging mounted on a Martian vehicle of 1000 pounds gross weight (GVW), to calculate pertinent performance values and then to observe how the performance would vary as these basic assumptions were changed.

For a vehicle of 1000 pounds gross weight, the following vehicle data are appropriate, as outlined in Section 6.

| | |
|---|---|
| Overall length | 120 in. |
| Wheel diameter | 34 in. |
| Crevice and step capability | 36 in. |
| Min. turn radius | 140 in. |
| Encroachment, max. | 7.3 in. |
| Energy for locomotion | 135 wh/km |
| Mobility subsystem weight | 400 lb |

## 9.1 MARS FLY-BY-WIRE MODE

The operation of the system is assumed to be as follows. The vehicle, standing still, orients its high gain antenna toward the earth, and automatically orients its stereo cameras in the desired direction. Pictures are read out of the cameras into the on-board data storage and processing subsystem where preprocessing, including data compression, if used, is done. Picture data are read out of storage into the telecommunications channel and transmitted to earth where they are received on a 210-foot DSIF antenna and transmitted over the Ground Communication System (GCS) to mission control at SFOF. Here the data are processed and analyzed to arrive at decisions as to the next command or command sequence. These are then read through the GCS into the uplink. The vehicle, in response to the commands, orients itself in the desired direction and executes a forward step of maximum distance compatible with vehicle safety.

In the following analysis, the overall average mission velocity achievable with a given control system is used as the measure of performance. Under the step-by-step fly-by-wire mode described above, the average velocity is the step distance divided by the total cycle time per step. This is, of course, subject to the effects of many random variables, most significantly those which arise from the terrain model itself. for example, obscuration effects. In the following analysis, these stochastic effects are ignored with the understanding that the numerical results will therefore be perhaps optimistic. They are useful mainly in providing an insight to the nature of certain trade-offs. Thus the terrain is assumed to be flat and level with obstacles (craters and rocks) randomly scattered thereon.

The distance at which an unobscured hazard can be detected depends upon the size of the hazard and the resolution of the detection system. (There are other very important factors, such as illumination conditions, which will be ignored for now.) Of the various kinds of hazards that must be detected, one of the more difficult is a hole. The difficulty arises from the foreshortening effect which causes a circular hole to appear as an ellipse whose minor axis is shorter the greater the distance from the sensor. Hazards such as boulders that rise above the surface do not suffer this effect and so, from this standpoint, constitute less of a problem. Lineal features such as crevices, although perhaps subtending very few resolution elements in one direction, provide element-to-element correlation which aids in their detection. Thus, for the following example we will consider the detection of a circular crater.

### 9.1.1 Geometry of the Imaging System

Figure 9-1 shows the geometric situation in the vertical plane. A camera mounted at height Hc is looking at a hole of diameter d, the leading edge of which is at a horizontal distance D from the camera. The vertical field of view of the camera is $\theta_V$. The hole

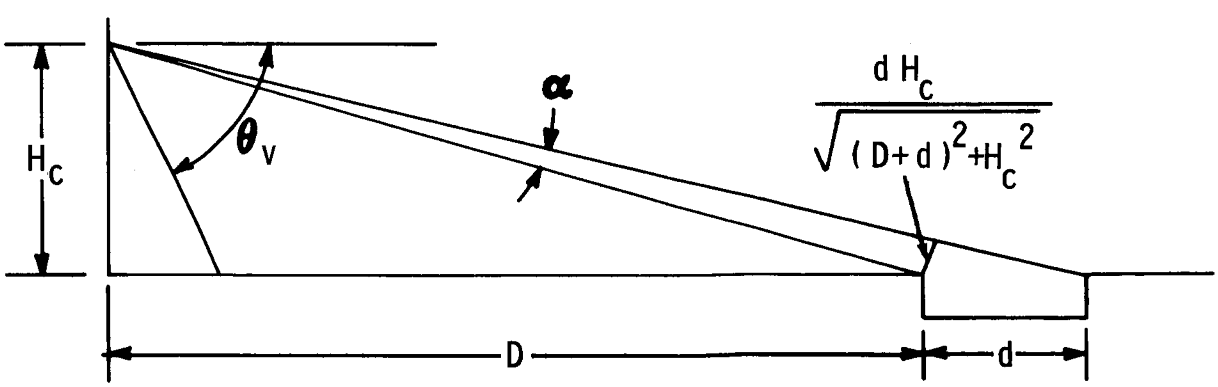



Figure 9-1 Detection Geometry in Vertical Direction

subtends angle $\alpha$ at the camera. The number n of vertical elements in the field subtended by the hole is

$$n = \frac{N_V \alpha}{\theta_V} \approx \frac{N_V \, dH_c}{\theta_V (D^2 + H_c^2)}$$

for $D \gg d$,

where $N_V$ is the total number of vertical elements in the field. If we assume that detection of the hole requires that at least $n_{min}$ elements be subtended, then

$$n_{min} \leq \frac{N_V}{\theta_V} \left[ \frac{dH_c}{(D^2 + H_c^2)} \right]$$

Solving the inequality for D gives the maximum distance at which the hole can be detected, as limited by vertical resolution.

$$D_V^2 \leq \frac{N_V \, dH_c}{n_{min} \theta_V} - H_c^2 \tag{9-1}$$

In the horizontal direction, shown in Figure 9-2, there is no foreshortening. The angle subtended at the camera is

$$\beta = 2 \arctan \left[ \frac{d}{\sqrt{D^2 + H_c^2} + d/2} \right]$$

and if $D \gg d$

$$\beta = \frac{d}{\sqrt{D^2 + H_c^2}}$$

Then the limiting distance at which the hole can be detected because of horizontal resolution is

$$D_H^2 \leq \frac{N_H^2 \, d^2}{\theta_H^2 \, n_{min}^2} - H_c^2 \tag{9-2}$$

where $N_H$ is the total number of horizontal resolution elements

$\theta_H$ is the horizontal field of view.

In the following we assume that $n_{min}$ elements must be subtended in both the vertical and horizontal directions for detection and therefore Equations (9-1) and (9-2) must both hold. Then the maximum distance Dmax at which detection can occur is

$$Dmax = \min (D_V , D_H) \tag{9-3}$$

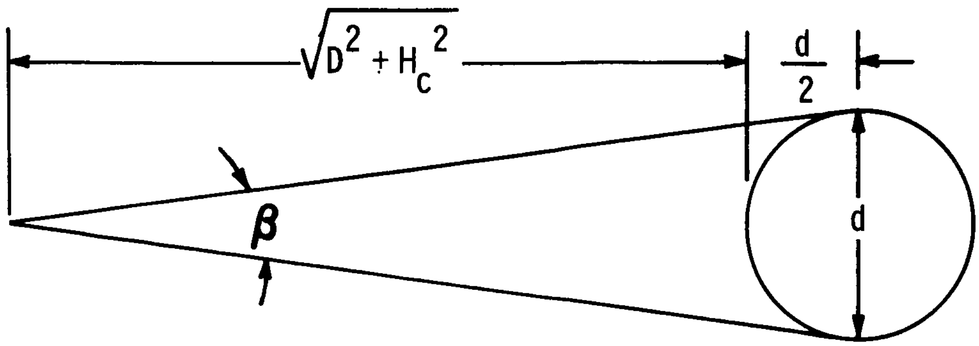



Figure 9-2 Detection Geometry in Horizontal Direction

This distance will normally be that determined by vertical resolution because of the foreshortening effect previously noted. In fact, it is easily seen that $D_V \leq D_H$ if

$$\frac{N_V}{\theta_V} \leq \left(\frac{N_H}{\theta_H}\right)^2 \left(\frac{d}{H_c\, n_{min}}\right) \tag{9-4}$$

The maximum safe step distance for the vehicle is less than the detection distance by the amount of the error $\Delta D$ in the measurement of that distance. Thus, if no obstacle is detected out to a measured distance D, then a step of distance $D_A = D - \Delta D$ is safe.

The geometry of the stereo measurement situation is shown in Figure 9-3. From this figure it can be shown that, for small angular errors, $\Delta\theta$

$$D_A = \frac{b}{2}\left(\frac{1 - b\,\Delta\theta/2D}{b/2D + \Delta\theta}\right) \tag{9-5}$$

where b is the stereo baseline.

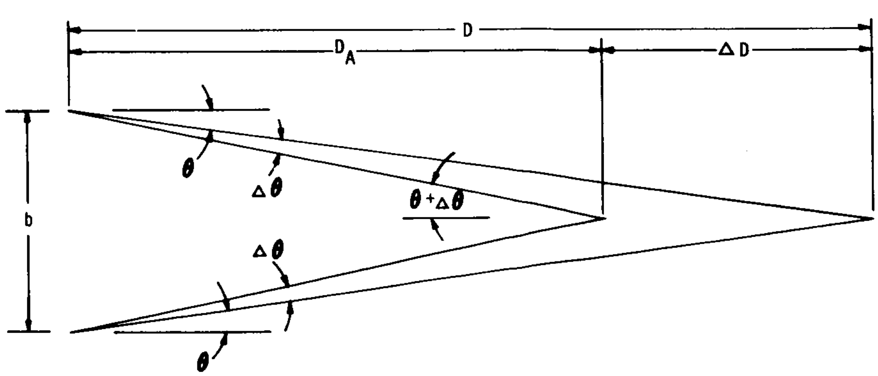



Figure 9-3 Stereo Geometry

The error $\Delta\theta$ may be composed of many independent errors (resolution, linearity, boresight, etc.) For the most part these errors arise because of practical design limitations or are the result of cost trade-offs. From the system performance point of view they are not subject to trade-off since performance is always enhanced by reducing the error.

One exception to this is the angular error that arises because of horizontal resolution. The actual angular position of a point in the field of view can be known only to within one half resolution element. In a horizontal field of $\theta_H$ radians having $N_H$ elements in the horizontal direction the angular error may then be as great as $\theta_H/2N_H$. Substituting this for $\Delta\theta$ in Equation (9-5),

$$D_A = \frac{b}{2}\left(\frac{1-b\theta_H/4\,DN_H}{b/2D+\theta_H/2N_H}\right) \tag{9-6}$$

For certain types of features, vertical quantization might also result in stereo measurement errors. These effects are ignored here, but must be considered in any complete analysis of the stereo imaging problem.

Thus, the maximum allowable step distance is determined by the distance D to which a clear path can be seen and by the horizontal resolution, which determines the measurement error. If the maximum detection distance is limited by vertical resolution, as is likely, then there might still be advantage in increasing horizontal resolution since this will increase the allowable distance $D_A$. In fact, from Equation (9-6) it is seen that, as $N_H$ tends to infinity, the allowable step tends to approach the detection distance. The cost, of course, is increased bit content in the picture and a resultant increase in communication time.

For $N_V/\theta_V$ exceeding 100 or so elements per radian the maximum value of $D_V$, given by Equation (9-1), will tend to approximate

$$D_V \approx \sqrt{\frac{N_V\,d\,H_c}{n_{min}\,\theta_V}} \tag{9-7}$$

Substituting Equation (9-7) in Equation (9-6), for D

$$D_A = \left(\frac{1-(b\,\theta_H/4N_H)\sqrt{n_{min}\,\theta_V/d\,H_c\,N_V}}{\sqrt{n_{min}\theta_V/\,dH_c\,N_V}+\theta_H/b\,N_H}\right) \tag{9-8}$$

### 9.1.2 Fly-By-Wire Operational Cycle

As suggested above, a trade-off occurs between the step distance and the control loop cycle time per step since step distance is increased at the cost of increased communication time. Total cycle time is comprised of several components. Starting with the completion of a step the following time increments must be taken into account.

| | | |
|---|---|---|
| $T_{LRO}$ | = | Time for orientation of long range sensors. |
| $T_{LRR/O}$ | = | Time for read-out of long range sensors into storage. |
| $T_{SDP}$ | = | Time for space-based data processing. |
| $T_A$ | = | Time to orient vehicle high gain antenna toward earth. |
| $T_{R/O}$ | = | Time for read-out of sensor data into telecommunication channel. |
| $T_T$ | = | Two-way communication transit time, Mars-to-Earth. |
| $T_{GCS}$ | = | Time to transmit data through the ground communication system. |
| $T_{GDP}$ | = | Time for ground-based data processing. |
| $T_{CR/O}$ | = | Time for read-out of commands into the uplink. |
| $T_{VO}$ | = | Time to orient vehicle in desired position. |
| $T_L$ | = | Time for actual locomotion |

Total cycle time $T_T$ is the sum of the above component times, and the average velocity realized over the surface of the remote body is

$$V_{AVG} = D_A/T_T \tag{9-9}$$

It is assumed in this analysis that it is desired to maximize $V_{AVG}$.

Before proceeding with the trade-off analysis, a brief discussion of the above time increments is in order. The analysis is worked out in most detail for the Martian fly-by-wire mode using stereo imaging. Other cases are considered by examining the ways in which they differ with this mode. For the Mars fly-by-wire, the following comments are relevant.

$T_{LRO}$ The time to orient the imaging sensors will generally be short with respect to other times encountered and will therefore be ignored.

$T_{LRR/O}$ This time will depend upon the type of sensor used, but in any event it will also be short with respect to other times, and will be ignored.

$T_{SDP}$ In the fly-by-wire mode, the only substantial space-based data processing envisioned is possible data compression. Initially, no data compression is assumed and $T_{SDP}$ is ignored.

$T_A$ Antenna orientation time is assumed to be inversely proportional to beamwidth, BW. Figure 9-4 shows the assumed relationship between antenna diameter, gain at 2295 MHz, and beamwidth at that frequency. The time to orient the antenna will clearly depend to a great extent upon the orientation technique, about which no specific assumptions are made. This time is arbitrarily assumed to be 900 seconds, for a 4-foot antenna, having a beamwidth of 8.5 degrees.

$T_{R/O}$ This time depends upon the information rate of the telecommunications channel which in turn depends upon range, transmitted power, and vehicle antenna gain and upon the total bits transmitted per cycle. Earth reception is assumed to be through the DSIF 210-foot diameter stations. The relationships between these variables which are assumed for this analysis are those shown in Figure 6-28.

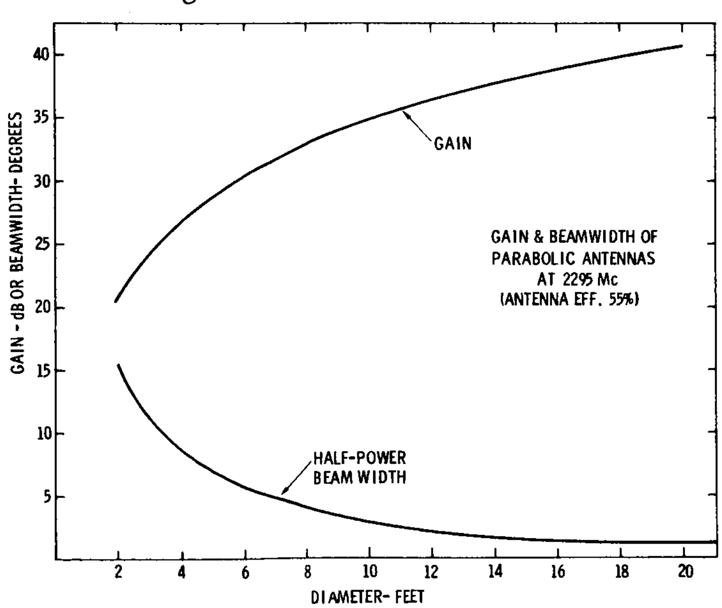



Figure 9-4 Antenna Gain and Beamwidth

These curves may be closely approximated by the relationship

$$I \cong 0.9\ PG \left(\frac{100}{R}\right)^2 \tag{9-10}$$

where

- $I$ is in bits per second
- $P$ is power in watts
- $G$ is absolute antenna gain
- $R$ is in millions of kilometers

The total number of bits transmitted is the product of the number of image elements, $N=N_V N_H$, the number of grey level bits per element, and a factor allowing for housekeeping (formatting, synchronizing, etc). Using a housekeeping factor of 1.15 and assuming eight grey levels, the total bits per cycle for a stereo pair is

$$Q = 6.9\ N_V N_H \tag{9-11}$$

and the readout time $T_{R/O}$ is

$$T_{R/O} = Q/I \tag{9-12}$$

$T_T$ Two-way transit time depends only upon the distance from Mars to the earth. $T_T$=6.67 R sec

(9-13)

$T_{GCS}$ The time to transmit data over the GCS from a DSIF receiving station to mission control at SFOF, is negligible for Goldstone which is linked to SFOF by a wide-band channel. For overseas sites, however the maximum projected bit rate[6] is 4800 bps, of which 10%, or 480 bps, is circuit overhead. Thus, the GCS effective data rate is 4320 bps. $T_{GCS}$ is then

$$T_{GCS} = Q/4320 \text{ sec} \tag{9-14}$$

In the calculations that were made it was assumed that both $T_{R/O}$ and $T_{GCS}$ are component times in the control cycle. This is equivalent to assuming that all data are received and stored at the DSIF receiving station prior to transmission into the GCS to mission control. Actually, time could be saved by simply relaying the data as it is received without storage if the incoming data rate is less than the GCS capacity. If the incoming rate is greater than GCS capacity, storage must be provided as a buffer to handle the data queue. In either case, the time arising from finite channel capacity would only be the greater of the values $T_{R/O}$ and $T_{GCS}$, rather than the sum as used herein. It will be seen that this saving would generally not affect the results significantly.

$T_{GDP}$ Time for ground data processing is dependent upon a great number of considerations. Lacking a detailed definition of the operations to be performed and their associated times, it is assumed for the Mars fly-by-wire mode that $T_{GDP}$ will average about 900 seconds per cycle.

$T_{CRO}$ Command readout into the GCS and the uplink will be subject to the same kinds of information rate restrictions as the data transmitted on the downlink. However, the total bit content is far less, and the uplink data rate can be made much greater because of the substantially greater transmitter power levels involved. It may be necessary to receive commands at the planet on an omni-directional (0 dB) antenna, but this is more than offset by the increased transmitter power.

$T_{VO}$ Vehicle orientation time will vary widely from cycle to cycle. It is assumed that a sequence of orientation commands is sent along with the locomotion commands and that an average of 300 seconds is used in executing these commands.

$T_L$ Locomotion time is the step distance $D_A$, divided by the vehicle locomotion velocity. While vehicle velocity is dependent upon several other parameters, it is assumed for Mars, that average locomotion velocity is 0.1 foot/second

Then

$$T_L = 10\, D_A \tag{9-15}$$

No allowance has been made in the above for transmission of engineering data about the status of subsystems nor for the transmission of scientific data. The former is ignored on the basis that it will generally involve substantially fewer bits per cycle than images. In other modes it may be a significant factor. Science data transmission is ignored since it depends upon the mission and may vary over a very wide range. The analysis therefore pertains only to the locomotion function and not to overall mission performance.

## 9.2 FLY-BY-WIRE TRADE-OFF ANALYSIS

For the 1000 lb vehicle assumed in this analysis, it seems reasonable that obstacles on the order of 2 feet or greater in size would be of interest. In addition, the following values are assumed for other variables in the above expressions.

| | |
|---|---|
| Camera Height, $H_c$ | 6 feet |
| Stereo baseline, b | 1 foot |
| Min. number of resolution elements subtended for detection, $n_{min}$ | 5 elements |
| Horizontal field angle, $\theta_H$ | 1 radian |
| Vertical field angle, $\theta_V$ | 1 radian |
| Range between Mars and Earth, R | $100 \times 10^6$ km |

The following parameter values are considered in the analysis

| | |
|---|---|
| Antenna diameter | 2 and 4 feet |
| Transmitted power, P | 10, 20, 50 and 100 watts |
| No. of vertical elements, $N_V$ | 100, 200, 500 and 1000 |
| No. of horizontal elements, $N_H$ | 100, 200, 500 and 1000 |

The calculated data appear in Table 9-1. The average velocities that appear in that table should not be construed to be those which would be realized in actual practice, since no account was taken of the nature of the terrain. In effect, these velocities are representative of what might be realized over a perfectly smooth, flat surface under the conditions assumed with respect to other parameter values. Their main usefulness lies in illustrating the nature of the trade-offs between power, antenna gain and image resolution.

### 9.2.1 General Conclusions of Fly-By-Wire Analysis

Certain interesting points can be derived from examination of the data in Table 9-1.

1. In very few cases is the time spent in actual vehicle motion greater than 10 percent of the total time.

2. While performance shows a slight tendency to peak with respect to horizontal resolution, the peak is not pronounced and further increases in horizontal resolution actually result in a decrease in performance which is sometimes quite sharp. In general it seems to be desirable to keep horizontal resolution moderately low. When horizontal

Table 9-1
MARS FLY-BY-WIRE ANALYSIS
RANGE = 100 x $10^6$ km

Antenna Dia., 2 feet, Gain G = 20.5 dB, Beamwidth = 15.25 degrees

| $N_V$ | $N_H$ | Q bits (000) | $D_V$ feet | $D_A$ feet | $T_A$ Sec | $T_{R/O}$ Sec P=10W. | 20 | 50 | 100 | $T_T$ Sec | $T_{GCS}$ Sec | $T_{GDP}$ Sec | $T_{VO}$ Sec | $T_L$ Sec | $T_{TOT}$ Sec P=10W. | 20 | 50 | 100 | Average Velocity, $V_{AVG}$ ft/hr P=10W. | 20 | 50 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 100 | 69 | 15.5 | 14.4 | 500 | 69 | 35 | 14 | 7 | 666 | 16 | 900 | 300 | 144 | 2595 | 2561 | 2540 | 2533 | 19.98 | 20.24 | 20.41 | 20.47 |
| | 200 | 138 | | 14.92 | | 138 | 69 | 28 | 14 | | 32 | | | 149 | 2685 | 2616 | 2575 | 2561 | 20.00 | 20.53 | 20.86 | 20.97 |
| | 500 | 345 | | 15.29 | | 345 | 173 | 69 | 35 | | 80 | | | 153 | 2944 | 2772 | 2668 | 2634 | 18.70 | 19.86 | 20.63 | 20.90 |
| | 1000 | 690 | | 15.4 | | 690 | 345 | 138 | 69 | | 160 | | | 154 | 3370 | 3025 | 2818 | 2749 | 16.45 | 18.33 | 19.67 | 20.18 |
| 200 | 100 | 138 | 21.9 | 19.76 | | 138 | 69 | 28 | 14 | | 32 | | | 198 | 2734 | 2665 | 2624 | 2610 | 26.02 | 26.69 | 27.11 | 27.26 |
| | 200 | 276 | | 20.8 | | 276 | 138 | 55 | 28 | | 64 | | | 208 | 2914 | 2776 | 2693 | 2666 | 25.70 | 26.97 | 27.81 | 28.09 |
| | 500 | 690 | | 21.45 | | 690 | 345 | 138 | 69 | | 160 | | | 215 | 3431 | 3086 | 2879 | 2810 | 22.51 | 25.02 | 26.82 | 27.48 |
| | 1000 | 1380 | | 21.7 | | 1380 | 690 | 280 | 138 | | 320 | | | 217 | 4283 | 3593 | 3183 | 3041 | 18.24 | 21.74 | 24.54 | 25.69 |
| 500 | 100 | 345 | 34.65 | 29.55 | | 345 | 173 | 69 | 35 | | 80 | | | 296 | 3087 | 2915 | 2811 | 2777 | 34.46 | 36.49 | 37.84 | 38.31 |
| | 200 | 690 | | 31.95 | | 690 | 345 | 138 | 69 | | 160 | | | 320 | 3536 | 3191 | 2984 | 2915 | 32.53 | 36.05 | 38.55 | 39.46 |
| | 500 | 1725 | | 33.5 | | 1725 | 863 | 345 | 173 | | 400 | | | 335 | 4826 | 3964 | 3446 | 3274 | 24.99 | 30.42 | 35.00 | 36.84 |
| | 1000 | 3450 | | 34.1 | | 3450 | 1725 | 690 | 345 | | 800 | | | 341 | 6957 | 5232 | 4197 | 3852 | 17.65 | 23.46 | 29.25 | 31.87 |
| 1000 | 100 | 690 | 49 | 39.4 | | 690 | 345 | 138 | 69 | | 160 | | | 394 | 3610 | 3265 | 3058 | 2989 | 39.29 | 43.44 | 46.38 | 47.45 |
| | 200 | 1380 | | 43.7 | | 1380 | 690 | 280 | 138 | | 320 | | | 437 | 4503 | 3813 | 3403 | 3261 | 34.94 | 41.26 | 46.23 | 48.24 |
| | 500 | 3450 | | 46.7 | | 3450 | 1725 | 690 | 345 | | 800 | | | 467 | 7083 | 5358 | 4323 | 3978 | 23.74 | 31.38 | 38.89 | 42.26 |
| | 1000 | 6900 | | 47.9 | | 6900 | 3450 | 1380 | 690 | | 1600 | | | 479 | 11345 | 7895 | 5825 | 5135 | 15.20 | 21.84 | 29.60 | 33.58 |

Antenna Dia., 4 feet, Gain 6 = 26.8 dB, Beamwidth = 8.50 degrees

| $N_V$ | $N_H$ | Q bits (000) | $D_V$ feet | $D_A$ feet | $T_A$ Sec | $T_{R/O}$ Sec P=10W. | 20 | 50 | 100 | $T_T$ Sec | $T_{GCS}$ Sec | $T_{GDP}$ Sec | $T_{VO}$ Sec | $T_L$ Sec | $T_{TOT}$ Sec P=10W. | 20 | 50 | 100 | Average Velocity, $V_{AVG}$ ft/hr P=10W. | 20 | 50 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 100 | 69 | 15.5 | 14.4 | 900 | 16 | 8 | 3 | 2 | 666 | 16 | 900 | 300 | 144 | 2942 | 2934 | 2929 | 2928 | 17.62 | 17.67 | 17.70 | 17.70 |
| | 200 | 138 | | 14.92 | | 32 | 16 | 6 | 3 | | 32 | | | 149 | 2979 | 2963 | 2953 | 2950 | 18.03 | 18.13 | 18.19 | 18.21 |
| | 500 | 345 | | 15.29 | | 80 | 40 | 16 | 8 | | 80 | | | 153 | 3079 | 3039 | 3015 | 3007 | 17.88 | 18.11 | 18.26 | 18.31 |
| | 1000 | 690 | | 15.4 | | 160 | 80 | 32 | 16 | | 160 | | | 154 | 3240 | 3160 | 3112 | 3096 | 17.11 | 17.54 | 17.81 | 17.91 |
| 200 | 100 | 138 | 21.9 | 19.76 | | 32 | 16 | 6 | 3 | | 32 | | | 198 | 3028 | 3012 | 3002 | 2999 | 23.49 | 23.62 | 23.70 | 23.72 |
| | 200 | 276 | | 20.8 | | 64 | 32 | 13 | 6 | | 64 | | | 208 | 3102 | 3070 | 3051 | 3044 | 24.14 | 24.39 | 24.54 | 24.60 |
| | 500 | 690 | | 21.45 | | 160 | 80 | 32 | 16 | | 160 | | | 215 | 3301 | 3221 | 3173 | 3157 | 23.39 | 23.97 | 24.34 | 24.46 |
| | 1000 | 1380 | | 21.7 | | 320 | 160 | 64 | 32 | | 320 | | | 217 | 3623 | 3463 | 3367 | 3335 | 21.56 | 22.56 | 23.20 | 23.42 |
| 500 | 100 | 345 | 34.65 | 29.55 | | 80 | 40 | 16 | 8 | | 80 | | | 296 | 3222 | 3182 | 3158 | 3150 | 33.02 | 33.43 | 33.69 | 33.77 |
| | 200 | 690 | | 31.95 | | 160 | 80 | 32 | 16 | | 160 | | | 320 | 3406 | 3326 | 3278 | 3262 | 33.77 | 34.58 | 35.09 | 35.26 |
| | 500 | 1725 | | 33.5 | | 400 | 200 | 80 | 40 | | 400 | | | 335 | 3901 | 3701 | 3581 | 3541 | 30.92 | 32.59 | 33.68 | 34.06 |
| | 1000 | 3450 | | 34.1 | | 800 | 400 | 160 | 80 | | 800 | | | 341 | 4707 | 4307 | 4067 | 3987 | 26.08 | 28.50 | 30.18 | 30.79 |
| 1000 | 100 | 690 | 49.0 | 39.4 | | 160 | 80 | 32 | 16 | | 160 | | | 394 | 3484 | 3400 | 3352 | 3336 | 40.71 | 41.72 | 42.32 | 42.52 |
| | 200 | 1380 | | 43.7 | | 320 | 160 | 64 | 32 | | 320 | | | 437 | 3843 | 3683 | 3587 | 3555 | 40.94 | 42.72 | 43.86 | 44.25 |
| | 500 | 3450 | | 46.7 | | 800 | 400 | 160 | 80 | | 800 | | | 467 | 4833 | 4433 | 4193 | 4113 | 34.79 | 37.92 | 40.10 | 40.88 |
| | 1000 | 6900 | | 47.9 | | 1600 | 800 | 320 | 160 | | 1600 | | | 479 | 6445 | 5645 | 5165 | 5005 | 26.76 | 30.55 | 33.39 | 34.45 |

resolution is kept fairly low, substantial gains are seen in increasing the vertical resolution, but even here a "diminishing returns" effect is evident. The implication is that, from the point of view of motion control, detection distance is more important than stereo distance measurement accuracy. This is, of course, because detection distance constitutes the upper bound on step distance. It is clear though that stereo accuracy must not be reduced so low as to introduce measurement errors which are a significant portion of the detection distance itself. It is also possible that stereo accuracy may be quite important in more rugged terrain where step distances are limited by the terrain features rather than by sensor detection distance. This tends to be offset however by the fact that stereo errors are inherently less at shorter distances. Figure 9-5 shows the stereo error arising from resolution as a function of distance. Here it is seen that when step distance is limited to, say, 10 or 20 feet by terrain features, the stereo error is small enough that it still does not constitute a serious limitation on performance.

3. Under the assumptions of the analysis regarding antenna orientation time, an increase in antenna gain is frequently a disadvantage since the improvement in data rate is more than offset by the increased orientation time. Since the assumptions were strictly arbitrary, it is not safe to draw firm conclusions from this apparent effect except to note that such an effect is in fact possible and should be carefully considered. It is quite possible that an improvement in performance can be realized through an increase in antenna gain only at the price of increased sophistication in the antenna pointing technique.

4. Increasing the transmitter power affects only the data rate and therefore $T_{R/O}$. Except for high resolution cases ($N_V N_H > 2 \times 10^5$) there is little gained by an increase in power. Even with greater resolution the increase in average velocity is not startling. Whether it is worthwhile or not would depend upon weight trade-offs that take into account the proportion of time spent in the high power transmitting mode. The maximum average velocity occurs with maximum vertical resolution, moderate horizontal resolution, high power and the low gain (20 dB) antenna. However, the performance computed for this case is not significantly better than that computed for minimum horizontal resolution and moderate power. For the case where $N_V = 1000$, $N_N = 100$, $P = 20$, and the two-foot diameter antenna, the total cycle time is apportioned in accordance with Table 9-2, Case II. Note that actual locomotion occurs only 12 percent of the total time.

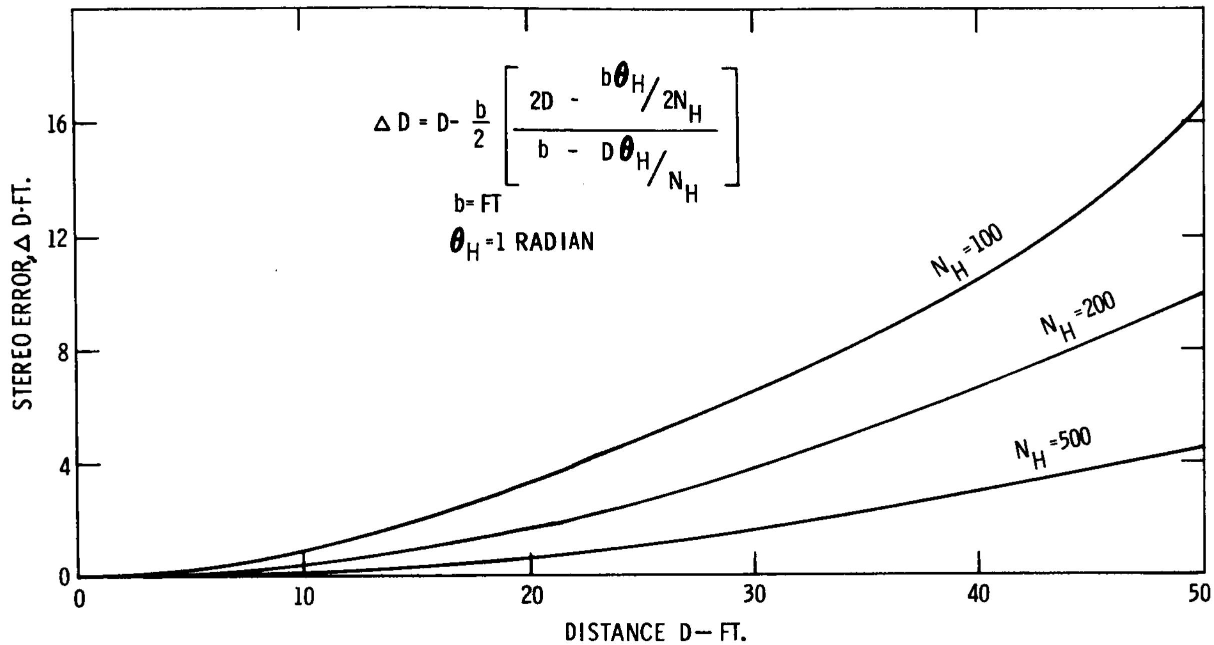



Figure 9-5 Stereo Error as a Function of Distance

Table 9-2
CYCLE TIMES

| Time Increment | Case I $55 \times 10^6$ km (%) | Case II $100 \times 10^6$ km (%) | Case III $400 \times 10^6$ km (%) |
|---|---|---|---|
| $T_A$ | 18.3 | 15.3 | 4.8 |
| $T_{R/O}$ | 3.9 | 10.6 | 52.9 |
| $T_T$ | 13.4 | 20.4 | 25.5 |
| $T_{GCS}$ | 5.9 | 4.9 | 1.5 |
| $T_{GDP}$ | 33.0 | 27.6 | 8.6 |
| $T_{VO}$ | 11.0 | 9.2 | 2.9 |
| $T_L$ | 14.5 | 12.0 | 3.8 |
| $T_{TOT}$ | 100.0 | 100.0 | 100.0 |
| $V_{AVG}$ | 52.0 | 43.44 | 13.5 |

### 9.2.2 Effect of Range

The distance from Mars to earth varies from about 55 to 400 million kilometers. This corresponds to a range of two-way communication transit time of about 366 to 2666 seconds. Compared with the values shown in Table 9-1, the readout times would vary with range from about one-third of the values shown to 16 times the values shown. Except for the higher resolution cases the results of Table 9-1 would not be substantially affected by lesser Mars-earth distances, since the readout times are generally not dominant and the 300 second reduction in transit time is only a small portion of the total. In general, the improvement in the high performance values in Table 9-1 would be about 10—15 percent at 55 x $10^6$ km and about 15—25 percent (or more in a few cases) at the low performance end, tending to reduce slightly the spread of performance levels shown.

On the other hand, increasing the communication distance to 400 x $10^6$ km makes transit time predominant at low resolution and readout time overwhelmingly predominant at the higher resolutions. The overall performance at the high end is reduced by a factor of about two to three. Where low-end performance is low because of image readout time the performance is reduced to nearly zero and where it is low because of other factors it is reduced by about half.

Figure 9-6 shows the manner in which performance varies with range for the example of Table 9-2. The end points of the fly-by-wire case are also broken down in Table 9-2, as Cases I and III. Here it is quite clear that, as range increases, the bulk of the time tends to go into reading data into the communication channel and into spanning the distance itself. Even if power is increased to 100 watts, over 60% of the time is devoted to these two functions. This then seems to be justification for going to a form of semi-automatic control wherein goals and general path plans are transmitted to the vehicle, but individual steering, start, and stop commands are generated by an on-board data processor directly responsive to sensors carried on the roving vehicle. The effect of this approach is discussed below, in Section 9.3.

### 9.2.3 Effect of Data Compression

The applicability of some form of data compression has been discussed. This technique, whatever its form of implementation, reduces the amount of data which must be transmitted over a link in order to convey a given amount of useful information. Data

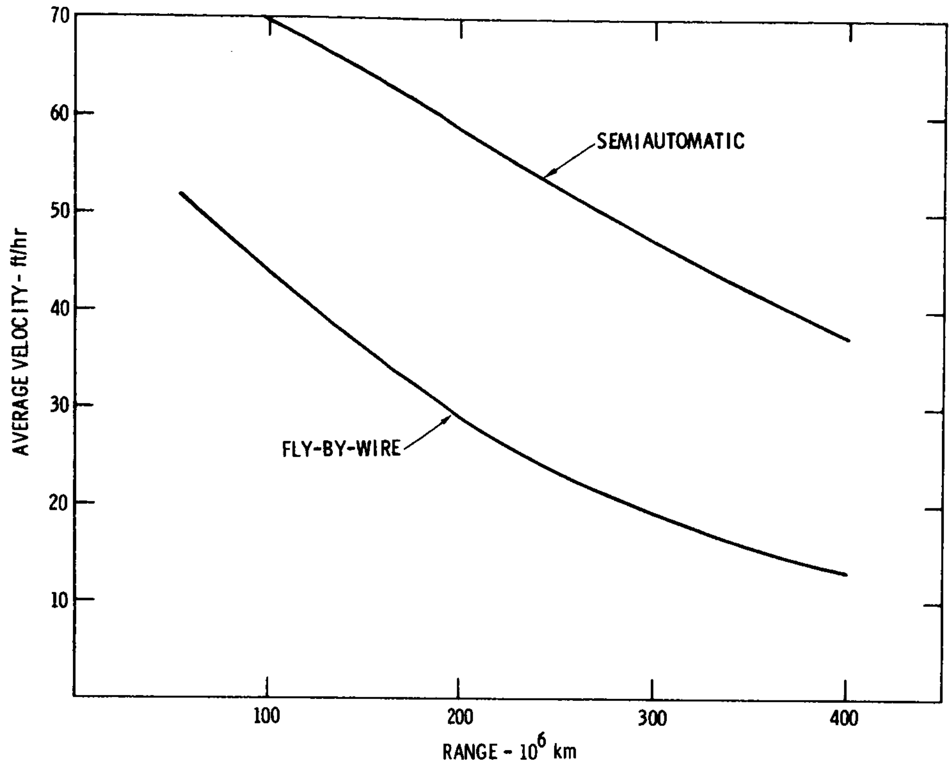



Figure 9-6 Performance vs Range

compression may be applied either before transmission from Mars to earth, thereby reducing both $T_{R/O}$ and $T_{GCS}$, or at remote DSIF stations to reduce $T_{GCS}$ only. In either case some penalty is paid in additional equipment at each end of the link and in slight time delays to process the data. For the example shown in Table 9-2, data compression on the vehicle by a factor of even two or three would yield great performance dividends at maximum distance by reducing $T_{R/O}$, but at moderate distances, compression factors as great as ten would have little effect.

Table 9-1 shows the more general situation, for a distance of 100 x $10^6$ km. If high resolution imaging is used, it appears that space-based data compression should be considered seriously.

Data compression at the DSIF stations would seem to have little to recommend it unless the space-based power-gain product is sufficiently great to make the ground communication system a relative operational bottleneck. This is the case only for the finest resolution and when either power or antenna gain or both are great.

### 9.2.4 Effect of Other Assumptions

It would be of interest to look briefly at the effect of some of the other assumptions made above. Raising the cameras affects the detection distance only, and, since detection distance is the upper bound on allowable step distance, this would seem to be advantageous. However, it should be noted that, under the approximation of Equation (9-7), the detection distance increases as the square root of camera height so that the advantage is modest. At any rate, six feet seems to be about the maximum feasible height for a vehicle of ten feet overall length. A larger vehicle could, of course, accommodate a proportionately greater camera height. It could also negotiate larger obstacles, so that detection distance for appropriate sized obstacles would be roughly proportional to vehicle length.

Stereo baseline affects stereo accuracy, but as seen from Table 9-1, the allowable step distance $D_A$ is never substantially less than detection distance $D_V$, so it would not appear to be particularly helpful from the control standpoint to increase the baseline, without also increasing the detection distance commensurately.

Once again it should be emphasized that the performance levels discussed above are possibly optimistic. They are based on an assumption of perfect stereo accuracy except for errors arising from resolution. More significantly the results assume a perfectly flat, smooth surface (but one which is not known ahead of time to be so). The introduction of slopes would seriously degrade the distances at which depressions could be detected and would in some cases obscure appreciable portions of terrain in the total field of view. Also, introduction of obstacles might require that more than one stereo pair be transmitted to establish a safe path, and might require steps much shorter than those calculated under the above assumptions.

## 9.3 MARS SEMIAUTOMATIC MODE

As was noted above, usually less than ten percent of the time is spend in actual locomotion in the mode analyzed above. In some cases this fraction of the time is about five percent. In the case showing maximum performance the total time spent in locomotion is only 13.4 percent of total cycle time. It is further evident from Table 9-2 that the most likely place to achieve a performance improvement, at least at the greater distances, is in reduction of the times associated with transmitting data to the earth and back, i.e., in $T_{R/O}$ and $T_T$. In Case I of Table 9-2, where the distance is

$55 \times 10^6$ km, it appears that an improvement might be realized by using a lower gain antenna also, although in this case, the assumed ground data processing time of 900 seconds predominates. Unless the actual ground processing time is broken down and carefully analyzed, it is not clear how or whether an improvement could be made here.

It does seem clear that at distances of $100 \times 10^6$ km and greater, it would be of great advantage to use the semi-automatic mode. In this mode it is assumed, for discussion purposes, that on-board sensors of some sort are capable of detecting and measuring the same distances as before, but that on-board data processing is used to generate individual motion control commands to effect a traverse to a destination via a route specified in at least general terms by ground control.

Let it be assumed that ten such steps are made on average between contacts with ground control, and that three stereo pairs are transmitted at the start of each cycle. Then $T_{R/O}$ is three times as great but occurs only one tenth as often. Likewise $T_A$ and $T_T$ occur only one-tenth as often. The control cycle consists of a major cycle and a minor cycle. The minor cycle, repeated ten times within each major cycle, consists of sensor orientation $T_{LRO}$, sensor readout $T_{LRR/O}$, space-based data processing $T_{SDP}$, space-based command read-out $T_{CR/O}$, vehicle orientation $T_{VO}$ and locomotion $T_L$. After ten minor cycles the major cycle is completed by a sequence consisting of sensor orientation $T_{LR/O}$, sensor readout (three stereo pairs), 3 $T_{LRR/O}$, space-based data processing $T^*_{SDP}$, (which differs from $T_{SDP}$, in that it is performed to condition data for transmission rather than to derive commands), antenna orientation $T_A$, data readout to the communication channel $3T_{R/O}$, transit $T_T$, ground communication $3T_{GCS}$, ground data processing $T_{GDP}$, and ground-based command readout, $T^*_{CR/O}$, (which differs from $T_{CR/O}$ in that it consists of a sequence of commands defining destinations and routes rather than detailed start, stop, and steering commands).

We assume that the space-based data processing time $T_{SDP}$, is comparable to $T_{GDP}$ in the fly-by-wire mode, i.e., 900 seconds. While it would no doubt take considerably longer to process picture data with a space-based computer than to do so on earth using humans, it is likely that some other form of sensor would be used or that processing would be done by some go-no-go technique such as the spatial filtering approach described in Figure 6-9. Space-based data processing might then take anywhere from negligible time to considerably more than 900 seconds depending on the approach. We shall assume 900 seconds. Under this assumption, sensor orientation, sensor readout and space-based command readout times would all be negligible in comparison. Vehicle orientation time is assumed to be the same as in the fly-by-wire case (300 sec) and locomotion time is still based on 0.1 foot per second. The minor cycle time then becomes ($1200 + 10\ D_A$). Ten minor cycles takes ($12000 + 100\ D_A$) seconds, and a distance of $10\ D_A$ is realized.

In the major cycle, the sensor orientation and readout times, space-based data processing time, and command readout time, are neglected in comparison to the other time increments in this cycle. Antenna orientation time is assumed to be the same as before. So also are the read-out time per stereo frame, and ground communication time per stereo frame. Ground data processing, including all decision times, is assumed to increase to 1800 seconds.

Table 9-3 summarizes the performance for $N_V = 500$ and 1000 elements, $N_H = 100$ elements, P = 10, 20, 50 and 100 watts, G = 20.5 and 26.8 dB and earth-Mars distances of 50, 100 and 400 million kilometers.

Compared with the fly-by-wire case there is, in general, a substantial improvement in calculated performance with this mode of operation. At $100 \times 10^6$ km distance the average velocity is up by at least 50 percent and in some instances by as much as 70 percent. For the case examined in Table 9-2, the improvement at this distance is 60 percent, and at $400 \times 10^6$ km the improvement is a factor of almost 3. While the improvement at $55 \times 10^6$ km is less, as expected, it is still a respectable 40 percent over the performance of the fly-by-wire. These improvements arise directly from the fact that time spent transmitting data from Mars to earth has been reduced to a negligible portion of the total time. Actual locomotion time has been increased to 20—25 percent of the minor cycle, which, in turn constitutes the bulk of time in the major cycle in most cases.

In addition to the general improvement in performance a few other interesting points may be noted. Once again the transmitted power level is relatively unimportant, provided that power is sufficient to prevent the data rate from being an operational bottleneck. Likewise increased antenna gain provides little in the way of performance improvement except at maximum range. At minimum range, a slight loss in performance is noted owing to the assumptions regarding antenna pointing time. The variation of performance with range has been plotted on Figure 9-6 for comparison with the fly-by-wire case.

# Table 9-3
# MARS SEMIAUTOMATIC ANALYSIS

Minor Cycle

$T_{TOT} = 1200 + 10\ D_A$

| $N_V$ | $N_H$ | $D_A$ ft | $T_{TOT}$ Sec |
|---|---|---|---|
| 500 | 100 | 29.55 | 1496 |
| 1000 | 100 | 39.40 | 1594 |

MAJOR CYCLE

Antenna Dia., 2 feet, Gain G = 20.5 dB, Beamwidth = 15.25 degrees

| Range ($10^6$ km) | $N_V$ | $N_H$ | 10 Minor Cycles Sec | $T_A$ Sec | $3T_{R/O}$ Sec P=10W. | 20 | 50 | 100 | $T_T$ Sec | $3T_{GCS}$ Sec | $T_{GDP}$ Sec | $T_{TOT}$ Sec P=10W | 20 | 50 | 100 | $D_{TOT}$ ft | Average Velocity $V_{AVG}$, ft/hr P=10W | 20 | 50 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 55 | 500 | 100 | 14960 | 500 | 313 | 157 | 60 | 31 | 366 | 240 | 1800 | 18179 | 18023 | 17926 | 17897 | 296 | 58.6 | 59.1 | 59.4 | 59.5 |
| | 1000 | 100 | 15940 | | 626 | 313 | 125 | 63 | 366 | 480 | | 19712 | 19399 | 19211 | 19149 | 394 | 72.0 | 73.1 | 73.8 | 74.1 |
| 100 | 500 | 100 | 14960 | | 1035 | 518 | 207 | 104 | 666 | 240 | | 19201 | 18684 | 18373 | 18270 | 296 | 55.5 | 57.0 | 58.0 | 58.3 |
| | 1000 | 100 | 15940 | | 2070 | 1035 | 414 | 207 | 666 | 480 | | 21456 | 20421 | 19800 | 19593 | 394 | 66.1 | 69.5 | 71.6 | 72.4 |
| 400 | 500 | 100 | 14960 | | 16550 | 8275 | 3310 | 1655 | 2666 | 240 | | 36716 | 28441 | 23476 | 21821 | 296 | 29.0 | 37.5 | 45.4 | 48.8 |
| | 1000 | 100 | 15940 | | 33100 | 16550 | 6620 | 3310 | 2666 | 480 | | 54486 | 37936 | 28006 | 24696 | 394 | 26.0 | 37.4 | 50.6 | 57.4 |

Antenna Dia., 4 feet, Gain G = 26.8 dB, Beamwidth = 8.50 degrees

| Range ($10^6$ km) | $N_V$ | $N_H$ | 10 Minor Cycles Sec | $T_A$ Sec | $3T_{R/O}$ Sec P=10W. | 20 | 50 | 100 | $T_T$ Sec | $3T_{GCS}$ Sec | $T_{GDP}$ Sec | $T_{TOT}$ Sec P=10W | 20 | 50 | 100 | $D_{TOT}$ ft | Average Velocity $V_{AVG}$, ft/hr P=10W | 20 | 50 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 55 | 500 | 100 | 14960 | 900 | 73 | 37 | 15 | 7 | 366 | 240 | 1800 | 18339 | 18303 | 18281 | 18273 | 296 | 58.1 | 58.2 | 58.3 | 58.3 |
| | 1000 | 100 | 15940 | | 146 | 73 | 30 | 15 | 366 | 480 | | 19632 | 19559 | 19516 | 19501 | 394 | 72.2 | 72.5 | 72.7 | 72.7 |
| 100 | 500 | 100 | 14960 | | 240 | 120 | 48 | 24 | 666 | 240 | | 18806 | 18686 | 18614 | 18590 | 296 | 56.7 | 57.0 | 57.2 | 57.4 |
| | 1000 | 100 | 15940 | | 480 | 240 | 96 | 48 | 666 | 480 | | 20266 | 20026 | 19882 | 19834 | 394 | 70.0 | 70.8 | 71.3 | 71.5 |
| 400 | 500 | 100 | 14960 | | 3840 | 1920 | 768 | 384 | 2666 | 240 | | 24406 | 22486 | 21334 | 20950 | 296 | 43.7 | 47.4 | 49.9 | 50.9 |
| | 1000 | 100 | 15940 | | 7680 | 3840 | 1536 | 768 | 2666 | 480 | | 29446 | 25626 | 23322 | 22554 | 394 | 48.2 | 55.4 | 60.8 | 62.9 |

## 9.4 USE OF OTHER SENSORS

The discussion above has assumed the use of stereo imaging in the fly-by-wire mode. Sensors in the semi-automatic mode were assumed to yield the same basic control information whatever their actual form might be.

In the fly-by-wire case, alternative sensing methods might include monoscopic pictures, either alone or in conjunction with a ranging device, and plot plan imaging. It does not appear that any of these approaches would make a substantial difference in the fly-by-wire performance calculated above. In most cases the alternative approaches would affect either the total information transmitted, and therefore $T_{R/O}$ and $T_{GCS}$, or the range measurement error, and therefore the allowable step distance $D_A$.

Use of monoscopic images alone would reduce the information in half, but would remove all range information except through the undesirable interpretive approaches described in Section 6. The savings in total information could be used to increase the resolution and therefore the detection distance. In order to compensate for the loss of range information, one of the ranging devices discussed in Section 6 could be used to supplement the monoscopic image. This, of course, adds to the total information. If the angular resolution of the ranging device were comparable to the resolution of the image there would probably be a net increase in total information even for very moderate range resolution. Alternatively, the image and the ranging device might both have somewhat poorer angular resolution, or the ranging device might be used selectively on objects in the video field which show peculiar characteristics such as sudden discontinuities in grey level, assuming that they could somehow be identified.

Implementation of such schemes might be difficult. Probably the main advantage in the use of a ranging device instead of stereo is in the relaxation that it would permit on certain other camera parameters. This, while important to system operation, would not show up in the above analysis, since degradation of performance from such factors was not considered.

## 9.5 ANALYSIS OF LUNAR FLY-BY-WIRE AND SEMIAUTOMATIC MODES

The analysis of performance of fly-by-wire and semi-automatic systems in the lunar case is subject to several very important basic differences. Fundamentally, these arise because of the much shorter distance over which control must be achieved.

Also, since the moon is not subject to major variations in distance from the earth, as Mars is, this need not be taken into account as a parameter.

Using the mean distance between the centers of the moon and earth, 384, 411 km, the two-way transit delay is about 2.6 seconds. Unpublished RCA analyses of the communication link on the SLRV showed that a high quality TV image could be transmitted from the moon in a 220 kHz bandwidth into the 210-foot DSIF dish with only 2 watts of transmitted power, and into the 85-foot dish with 10 watts. In both cases a 20 dB vehicle antenna was assumed. Another source (30) has projected a data rate from the moon in the early 70's of $10^6$ to $10^7$ bits per second. Thus, it would appear that transit time and time to readout images into the downlink are not so great as to render insignificant the times allotted to sensor orientation and readout as in the Martian case. In fact, the rf channel data rate is sufficient to permit direct readout of the sensor at its maximum rate without buffer storage. The above mentioned RCA analyses allow about 5.5 seconds for a complete stereo sequence using a vidicon sensor. Actual frame readout (each frame of the stereo pair) was 1.6 seconds, which is based on a 500 line raster read directly into an rf channel having 125 kHz bandwidth. Thus, the vidicon readout is the limiting operation as far as time is concerned.

Of course, if ground-based data processing and decision time is comparable to that postulated above for the Martian case, none of the above times would be relatively significant. One would then have a situation where a locomotion cycle would consist essentially of a period of decision-making and a period of locomotion with all additional operations taking negligible time. At 0.1 feet per second locomotion speed the average velocity would then be

$$V_{AVG} = \frac{3600\, D_A}{900 + 10\, D_A} \quad . \quad \text{ft/hr} \qquad (9\text{-}16)$$

This is plotted in Figure 9-7.

The arbitrary assumption of 900 seconds for data processing and decision-making is probably not realistic. In the Martian case it did not affect the results because the 900 seconds did not constitute the bulk of the cycle time. In the above lunar situation, however, it constitutes from about 2/3 to 9/10 of the total time and should therefore be considered more carefully.

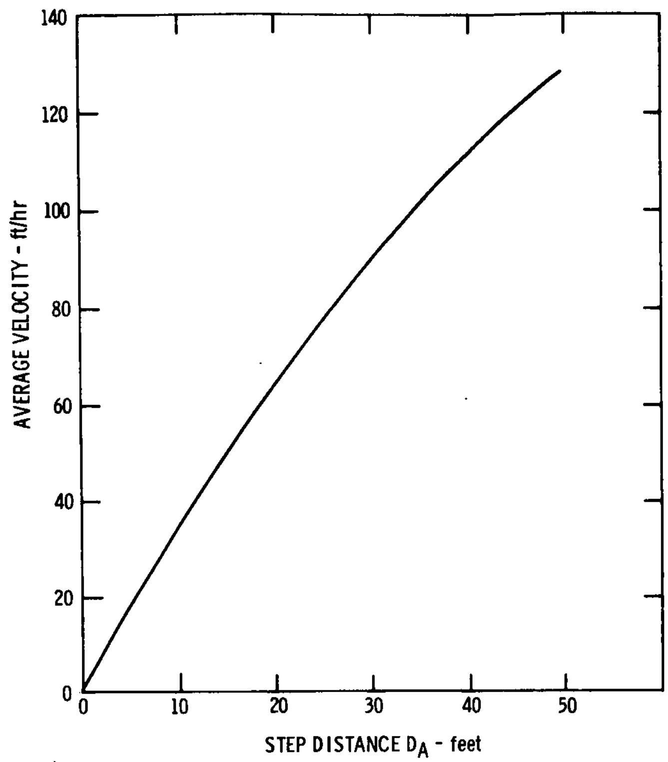



Figure 9-7 Average Velocity vs Step Distance
Lunar Case with Long Decision Time

In the SLRV Control Study,(1) it was found that operators could view stereo pictures and issue commands at a rate of one every five or ten seconds. The step distance used in these tests was on the order of three feet, and the average vehicle velocities were about 420 to 480 feet per hour. The nominal locomotion speed of this vehicle was 0.75 feet per second, indicating motion about 18 percent of the time.

A typical fly-by-wire lunar locomotion cycle in a moderately smooth terrain might break down as follows:

| | | Sec |
|---|---|---|
| 1. | Orient Antenna | 2.7 |
| 2. | Position camera | 4.2 |
| 3. | Monoscopic image | 3.7 |
| 4. | Position camera | 4.2 |
| 5. | Monoscopic image | 3.7 |
| 6. | Position camera | 4.2 |
| 7. | Stereo image | 5.5 |
| 8. | Decision time | 10.0 |
| 9. | Command readout and transmit | 2.0 |
| 10. | Steer | 3.5 |
| 11. | Step forward (one wheel revolution) | 12.0 |
| | | 55.7 |

This sequence assumes that the picture-taking process is automatic, i.e., no special commands need be sent. If separate commands must be sent for each camera position and picture, it might add up to about 4 seconds. Also, the locomotion portion is based upon a step of one wheel revolution at 0.75 feet per second using the 1000 lb vehicle having a wheel diameter of 34 inches. Thus, we note that a step of 8.9 feet is accomplished in a total cycle time of 55.7 seconds for an average speed of 575 feet per hour. Depending upon actual procedures used in the SFOF, the command readout time could be considerably more than that allotted above.

Quite likely the decision time would be a function of the step distance. Before committing the vehicle to longer steps the operator would want to study the data at hand more thoroughly. This could give rise to a trade-off situation between step distance and decision time. Although this might be interesting to pursue, there seems to be insufficient data available at present to do realistically. This might be a fruitful area to investigate experimentally.

Note in the above fly-by-wire sequence that actual locomotion takes place a little more than 20 percent of the time. If one were to assume some form of semi-automatic operation similar to that described for the Martian vehicle above, there might be some improvement in this performance. The amount of improvement would be highly sensitive to the assumptions made with respect to on-board decision times, etc. It seems likely that any implementation of the semi-automatic mode for the lunar case would use rather rudimentary sensors and simple decision processes. An example of a control cycle under assumptions similar to those of the Martian case (i.e., ten minor cycles per major cycle) is shown below.

A. Minor cycle.

| | Sec |
|---|---|
| 1. Scan sensors | 5.0 |
| 2. Decision time | 2.0 |
| 3. Steer | 3.5 |
| 4. Step fwd (one revolution) | 12.0 |
| | 22.5 |

B. Major cycle.

| | Sec |
|---|---|
| 1. Orient antenna | 2.7 |
| 2. Position camera | 4.2 |
| 3. Stereo image | 5.5 |
| 4. Orient camera | 4.2 |
| 5. Stereo image | 5.5 |
| 6. Decision time | 180.0 |
| 7. Command readout and transmit | 4.0 |
| 8. Ten minor cycles | 225.0 |
| | 431.1 |

For this example, there is a 22 percent reduction in the time to take ten steps and the average speed is nearly 750 feet/hour. The greatest single item in the cycle, however, is the ground-based decision time which is a purely arbitrary value.

## 9.6 IMPLICATIONS OF THE ABOVE WITH RESPECT TO MISSION CAPABILITIES

It is of interest to examine the above results with respect to their implications regarding overall missions. Recognizing that the average velocities calculated above are probably quite optimistic, one might nevertheless consider what maximum overall mission coverages could be realized.

In the case of Mars, the planet rotates with a period of about 24-2/3 hours. Then direct communication with the earth is possible for only a 12-hour period each day. This period is further reduced by the considerations cited in Section 2, and may be as low as four hours in some cases.

Typically, in the fly-by-wire case, the average locomotion velocity at $100 \times 100^6$ km was about 43 feet per hour and at $400 \times 10^6$ km this is down to 13 feet per hour. Thus, over a six-month interval, one might realize an average velocity of 24 to 30 feet per hour. This would amount to roughly 10 km maximum over a six-month mission. With the semiautomatic mode, the velocities calculated were on the order of 40 to 70 feet per hour at the same ranges. This would result in six-month travel distances of about 18 km. However, under the assumptions of the analysis, nearly half the time was spent in on-board data processing. It thus seems apparent that on-board data processing must either be done in parallel with other functions or it must be reduced drastically below the value assumed above. Perhaps also, the vehicle locomotion velocity could be several times the 0.1 foot/second assumed above, during most of the mission. It seems not too unlikely that overall distances of around 200 km or more could be achieved by choosing sensors which are compatible with rapid data processing techniques. This might be improved even further by judicious strategies which might, for example, plan paths with segments which end at high points. Considerable analysis is still needed to see what possibilities exist in such approaches.

For the moon, the velocities which were projected above were commensurate with considerably better overall mission performance. Here, the daily window is restricted by rotation of the earth rather than the survey body. If one assumes all operations through the Goldstone complex, there are about ten hours maximum per day during which operations could be conducted. This would permit distances of about 2 km per earth day under the above assumptions in the fly-by-wire mode and about 3 km in the semiautomatic mode. The amount by which these values would be degraded by terrain obscuration effects is unknown, but should be the subject of additional analysis.

# 10.0 MISSION ANALYSIS

In the previous section, the fly-by-wire and semiautomatic modes were analyzed to provide insight to the nature of the trade-offs that occur and to identify the significant variables and parameters in each case. In order to permit the subject to be treated quantitatively, a highly simplified terrain model was assumed, viz., flat, level terrain. In this case, the range of the sensors, and not the terrain, tended to be the limiting factor in performance.

In any real lunar or planetary environment it is, of course, highly unlikely that such an idealized situation would be obtained. Even moderately rolling terrain results in significant fractions of the surface being obscured from view from any single vantage point. Hazards, when they occur, do not necessarily occur at the limit of the range of the sensors. If it is assumed that the vehicle will never be committed to enter a region that has not been evaluated and certified from the point of view of vehicle safety, then it will usually not be possible to take the maximum step permitted by sensor capability in each cycle. Under such conditions the performance of the system, in terms of average velocity, might suffer greatly.

A thorough analysis of this type of situation was not undertaken in this study owing to limitations of time and funding. However, thought was given to the approaches that might be taken. The following discussion deals with this question.

## 10.1 MISSION SIMULATION

One useful approach to the evaluation of RVMC performance is the simulation of a roving vehicle mission under a variety of assumed conditions. Here, a mission is not to be construed as a set of scientific tasks to be accomplished, but is rather the traversal of the surface from one given point to another (Function F1 in Section 3). Because of the many stochastic influences on a mission, the measures which are applied must be, for the most part, statistical. This leads to a Monte Carlo-type analysis.

Figure 10-1 illustrates in a gross manner, the typical flow of an analysis of this kind. The rectangular blocks represent inputs and outputs of subanalyses which, in turn, are designated by circles. Subanalysis A is basically deterministic, and combines the

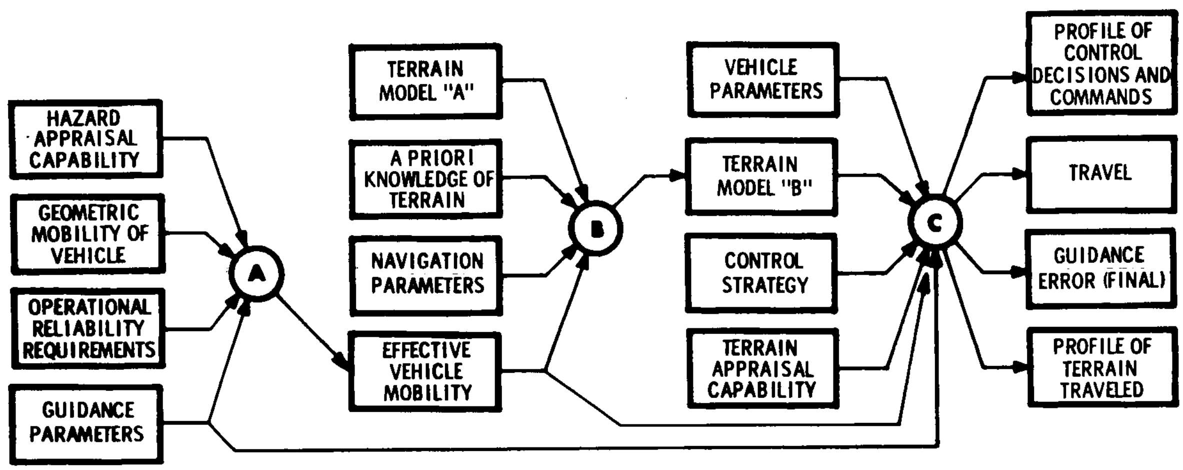



Figure 10-1 Simplified Analysis Flow Diagram

fundamental geometric mobility of the vehicle with limitations imposed by sensor perception capabilities, control uncertainties in positioning the vehicle, slip of the wheels, etc., and risk or other operational factors, to arrive at a degraded set of mobility parameters constituting what is termed the effective vehicle mobility. Subanalysis B then relates the effective vehicle mobility to a model of the terrain, expressed in terms of statistical parameters, and measures of the navigational capabilities of the system and a priori knowledge of physical features of the terrain, to evolve a modified statistical terrain model which encompasses those features which are significant to the particular vehicle of interest. Finally, in Subanalysis C, the movement of the vehicle across the terrain is simulated by combining the simplified terrain model with a control law or strategy and the characteristics of the sensor/appraisal mechanization and the vehicle. The essential results of Subanalysis C are the actual travel distance (as compared with the effective traverse distance) and the time required. Secondary results might include a typical profile of control actions, subsystem duty cycles, and actual terrain covered. These data can be usefully applied to analyses of power and energy requirements, ground procedures, etc.

## 10.2 SUBANALYSIS A

In Subanalysis A, the basic geometric mobility of the vehicle (as expressed in terms such as those presented in Section 6.4) is degraded by factors relating to the inherent ability to detect and evaluate hazards and the ability to make the vehicle go where one directs it, or to do as one commands it. In the SLRV Control Study[1] these factors were referred to as perception margins and control margins. The perception margin includes allowance for sensor errors, resolution, and perhaps subjective aspects of perception. Control margin may arise from unknowns such as wheel slip or from the inherent coarseness of control that arises from a limited repertoire of commands. One might further degrade the geometric mobility by arbitrary safety or operational factors.

The quantitative evaluation of effective vehicle mobility is an extremely subtle, complex task involving the sensing, reporting, appraisal, and decision functions, and including the human operator, where used. It is not at all certain that this analysis can be done in a completely objective manner. More likely, it would involve a great deal of judgment, and it should, of course, be aided by properly directed experimental studies.

## 10.3 SUBANALYSIS B

In this analysis, the terrain model is simplified to include only those factors which are pertinent to the actual motion control problem. Thus, beginning with an abstract model of the terrain which is independent of the roving vehicle, one can first remove all features which are too small relative to the vehicle size to constitute a significant hazard or otherwise to affect motion control. Where a priori information, say from orbiter photos, is available it might also be possible to remove large features from the model, depending upon the navigational capability to locate the vehicle with respect to these features and to avoid them altogether.

### 10.3.1 Terrain Modeling

The terrain models which are described in Section 3 were purely qualitative and therefore not suitable for use in an analysis of this kind, especially where one might wish to use a computer simulation. Consideration has been given to the manner in which quantitative models might be generated, although no attempt was made to do so under this study.

There are many methods which may be used to characterize surface properties quantitatively. Terrain such as described for Model 1 of Section 3 may be represented by a contour map which provides quick recognition of general terrain features and brings out unique topographical features of a particular region. However, it is applicable only to that region and gives information which is not of interest to general mobility while failing to provide a simple quantitative characterization of the aspects which do affect mobility.

Another method, which recognizes the statistical nature of terrain characterization, is the slope histogram or slope probability distribution. Such a characterization depends strongly upon the sampling interval used. However, it fails to provide sufficient information for control purposes because it gives no information about the dependence of the slope at any given point upon the slopes at nearby points. This is not a serious limitation on a scale of a kilometer, since such dependence is probably tenuous at this distance. The limitation on the scale of a few vehicle lengths is serious, however, especially in the case of gently rolling terrain where abrupt changes in terrain are unlikely.

Another similar approach which has been taken is to characterize the probability distribution of the derivative of the slope (or the curvature). This approach suffers from the same problem as analysis of slope statistics, namely, that it fails to account for correlation between the curvature at adjacent points. Since the correlation is probably less for the curvature than it is for the slope the latter characterization is in this sense preferable. However, this characterization is very cumbersome in use, particularly in regenerating a terrain model for mission simulation.

An approach which accounts for the statistical nature of the terrain and also incorporates the effects of correlation is one which characterizes the terrain in terms of its power spectral density, which is derived as the Fourier transform of the autocorrelation function under certain assumptions which can usually be satisfied practically, at least for the purposes under consideration in this discussion. This approach provides a quick quantitative comparison between terrains. Previous analyses of a wide variety of terrains indicate a tendency for the spectral density of all these terrains to have approximately the same form, viz., they follow an inverse power relationship with spatial frequency. A rough approximation is obtained by using a minus 5/2 power law. The rms roughness in the size range of interest is simply the square root of the integral of the spectral density over the corresponding range of spatial frequencies.

Thus, a vehicle having an overall length of two meters and a wheel diameter of one-half meter might reasonably be affected by terrain roughness in the range of 0.2 meter to 20 meters, corresponding to a spatial frequency range of 0.05 to 5 cycles per meter. A terrain of this type can be simulated by feeding the output of a white-noise generator into an appropriately shaped lowpass filter.

Small craters on the surface of the moon have been considered by several investigators since the Ranger series of missions. These have been characterized in terms of their cumulative frequency distribution per unit area by expressions of the form $N = aD^b$, where N = number of craters with diameters greater than D per unit area and a and b are empirically determined constants. The exponent, b, consistently takes on a value of approximately -1.8. Crater distributions consistent with terrain Model 1 would result from use of $a = 10^5$; distributions consistent with Model 2 from $a = 5 \times 10^6$; and distributions consistent with Model 3 from $a = 10^8$, where D is in meters and a is in craters per 10 $km^2$.

It appears that useful terrain models could be generated by a computer from the above considerations. Starting with an underlying terrain having a spectral density over the range of interest which can be characterized by two parameters (level and slope), one could overlay this first with craters having a size distribution characterized as above and a Poisson area distribution. This would be followed by a particle overlay having an appropriate size distribution and Poisson area distribution.

More thought must be given to this approach before it would be useful. Among the areas that need to be further developed are those of spectral characterization in two dimensions and generation of two-dimensional models from an appropriate characterization. Another is the problem of a rationale for the superposition of two or more craters or rocks at the same point or at points which are relatively close together. One might also incorporate soil parameters into the model so as to enable traverse power profiles and energy budgets to be analyzed.

## 10.4 SUBANALYSIS C

This constitutes the actual traverse simulation. The simplified terrain model derived in Subanalysis B is assumed. From any given vantage point this terrain model will generally cause some of the surrounding terrain to be obscured from the view of the sensors. The sensors themselves, in combination with the entire machinery of terrain appraisal, will further limit the ability to evaluate a situation and to take appropriate control action.

The control actions derive from an established control law or strategy which provides more or less standardized responses to the various situations which might be encountered.

The control strategy must take into account the distance at which the sensors are effective in detecting and evaluating hazards and the effective mobility of the vehicle. Generally, any control strategy will follow a logical flow similar to that illustrated in Figure 10-2. The system detects a hazard and normally evaluates the hazard. If negotiable, the control system (possibly involving a human operator) formulates a plan to proceed over the obstacle and, if not negotiable, the system seeks an alternative path. If such a path is found, a procedure is mapped out and the vehicle proceeds. If not, either a new goal is chosen or the mission is aborted.

The formulation of a plan in each instance depends upon the effective mobility and the spatial relationship of the hazard and the vehicle at the time of hazard evaluation. If, for example, the vehicle is equipped only with short-range tactile sensors, detection and evaluation cannot occur until the vehicle is in contact with the hazard. In this case, if avoidance of the obstacle is in order, it must back off and maneuver in some manner

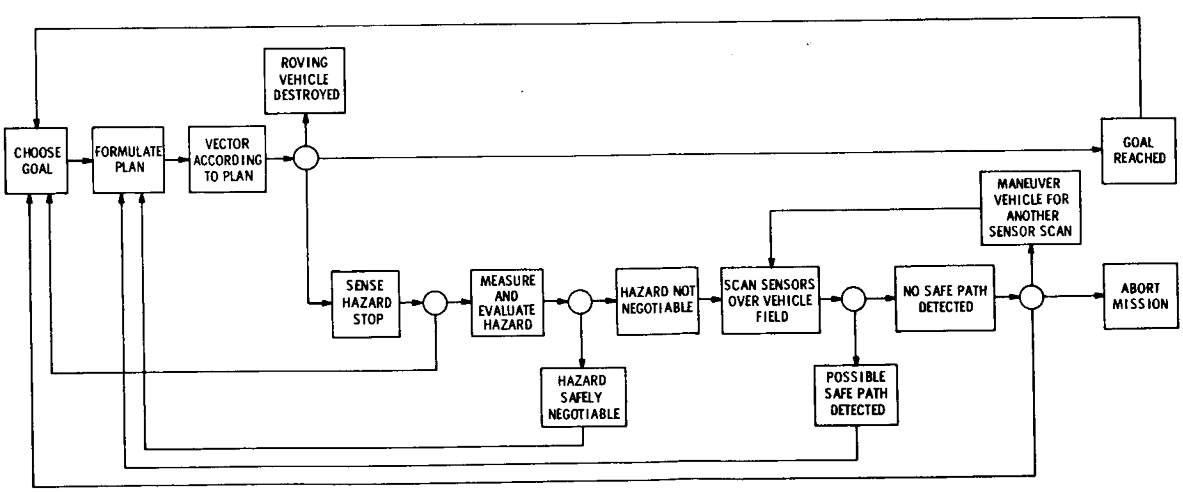



Figure 10-2 Typical Control Strategy

around the obstacle, eventually resuming its progress toward the original goal. Associated with the avoidance maneuver is a penalty in terms of distance traveled and commands issued. The magnitude of the penalty depends upon the size of the obstacle, the strategy used to avoid it, and the distance from the hazard at which the avoidance maneuver is initiated (which is bounded at the upper end by the sensor capabilities). The total distance traveled is the traverse distance plus the sum of all of these penalties.

## 10.5 TYPICAL COMPUTER SIMULATION

With the above general points as a foundation, the following discussion is representative of the manner in which a simulation might be carried out. It is not offered as a recommended or preferred approach, since a great deal more thought needs to be devoted to the subject. Nevertheless, it should serve to illustrate what could be done.

### 10.5.1 Computer Simulation of Semiautomatic Mode with Minimal Path Planning Capability

The general procedure is as follows.

a. Generate a computer model of the terrain, T (x, y). This would, for example, give elevation and perhaps soil parameters at every point in the region of interest. Alternatively, a simpler version for initial analysis might simply divide the plane into impassable and passable areas. This model might be generated in this way:

   1. A given area, A, is assumed and points are located on A by cartesian coordinates (x, y).
   2. A given numerical distribution of obstacles according to size and type is given and ordered, giving a set of numbers $N_1$, $N_2$, ...., $N_k$.
   3. The machine places the obstacles on centers $(x_i, y_i)$ whose coordinates are generated randomly.
   4. The machine outputs a description of the terrain (probably by square units) identifying all areas which contain some portion of an obstacle. (In more sophisticated models the type and dimensions of the obstacles could be identified for use in obscuration calculations. Also the obstacles could be superimposed on rolling terrain described by power spectral density for more sophisticated analyses.)

b. A starting point is picked at random and checked to insure that it is in an accessible area. (Accessible is to be interpreted as meaning that a circle of radius equal to the distances from the center of the vehicle to its most extreme point measured in the horizontal plane contains no square containing any part of an obstacle; i.e., the vehicle can be safely centered on the point with random orientation.) If not the computer generates another point, checks it, etc., until an accessible starting point is chosen. Then a destination point is chosen at random from the points on the circle with a given radius, and it is checked for accessibility, etc., until an accessible destination point has been designated. This identifies a straight line on the plane giving the desired traverse.

c. The RV begins at the starting point, headed toward the destination point with a given sensor range capability. Heading = $\emptyset_0$; starting point = $P_0$; destination point = Q. The computer determines the rectangular area of width W (vehicle width), and length L (vehicle length), centered on $P_0$ aligned with $P_0Q$. It adds to this the area covered (ideally) by the sensors (obscured areas could be computed and subtracted from the ideal coverage in more sophisticated analysis).

d. If none of the areas covered in (c) contains an obstacle, the vehicle moves along the line $P_0Q$ by increments the length of which is consistent with the observed free path length, computing areas as in (c) with each increment, except that the areas are located with respect to P (the current vehicle position) until some obstacle is detected.

e. If the area associated with (c) or (d) contains an obstacle, a programmed maneuver is followed. The maneuver can vary widely according to vehicle capabilities and characteristics and according to control strategy. It is carried out by small increments and the areas are calculated as in (d), but now the axis of the areas is headed in the direction of the vehicle heading $\emptyset$.

f. This continues until Q is reached. The history of P and $\emptyset$ is recorded together with cumulative path length and the number of vehicle commands according to type. If a time penalty is assigned for each command type a running time total may also be recorded.

g. New runs using different $P_0$ and Q, or using other terrains generated from the same statistics should be run and Monte Carlo-type convergence looked for with each vehicle, operating mode, etc.

Such runs provide a check on the analytic simulation and allow the determination of the effects of terrain parameters, control strategies, sensor range capabilities, etc. Analysis can also be extended to include more sophisticated systems using complex path planning strategies.

The effect of guidance and navigational errors on the operational mode above will be mainly to increase the distance traveled somewhat, since guidance is not depended upon to maintain a particular path, and encounters with obstacles are random. Thus the guidance analysis may be conducted separately to obtain an expected increase in travel due to guidance error. The travel distance per unit traverse must be adjusted accordingly. The travel speed is utilized to compute a time penalty associated with guidance error and a corrected mission speed.

### 10.5.2 Simulation With Path Planning

If significant path planning capability is assumed to be present the above analysis must be modified to include this capability. An essential part of this analysis is to determine the kind and amount of information which would be available to the controller. Thus, not only must masking effects be considered, but also the resolution and measurement capabilities of the sensor system should be used to determine the quality of information available. This is necessary in general in order to make maximum use of the information available, since detectability of obstacles depends upon range, the obstacle dimensions, and the obstacle type. Therefore, partial information will possibly be available for large areas where enough information to determine that a safe path does or does not exist is not available.

Then it is necessary to devise criteria for path selection (or a control strategy). The process is, in a sense, a multipoint decision problem where the information available is incomplete and/or possibly statistical in nature. The problem of identifying an optimum (or, more realistically, a "good") control strategy might therefore be amenable to a dynamic programming approach. Given a policy it should not be difficult in principal to apply it in a mission simulation.

In discussing path planning strategies there are perhaps two primary characteristics to consider, viz.:

1. elegance – referring to the shortness of the path selected from $P_o$ to Q and possibly to other characteristics such as average roughness of the chosen path.
2. economy – referring to the ease of implementing the strategy and to the shortness of the search procedure in locating the path.

In any strategy some criteria as to the value of alternate path segments must exist. These may be simple, such as

1. maximize distance traveled toward goal, or
2. minimize distance remaining to goal.

They may also include a number of considerations such as considering the existence of known obstacles between endpoints of a given path segment and the goal, weighing of rms path roughness, preference of a path segment ending with an unknown to one ending at a known hazard, or considering the closeness of approach to known hazards along the path segment.

Guidance errors become important during the path planning stages affecting path planning directly. Hence guidance characteristics should be included throughout the analysis – at least by including allowances for guidance error in computing the relative safety of possible paths. The cumulative effects must be included if complex paths are to be mapped out from knowledge of the terrain at some point.

# 11.0 RECOMMENDATIONS FOR FUTURE ANALYSIS

The present study has laid a philosophical foundation for more detailed consideration of roving vehicle motion control. It has not resulted in recommendations for specific system mechanizations, nor was it intended to. The problem has been thoroughly defined in terms of general constraints and requirements. To these must be added any special requirements which are peculiar to a particular mission.

The spectrum of possible approaches has been examined and their relative advantages and weaknesses have been evaluated to the point where certain broad conclusions can be reached. These have been stated in Section 1. Before these conclusions can be interpreted in terms of specific hardware designs, however, additional analysis would be desirable. The specific areas where analysis is most needed are discussed in the following paragraphs. There are also a number of questions related to the motion control problem which are not answerable by strictly analytical methods. A carefully planned and executed experimental program is needed to supplement these studies. Such a program has been suggested in a separate report[37] submitted under this contract.

First, as stated in this report at several places, it seems probable that terrain geometry itself will be the factor that most seriously restricts the decision-making capability of the RVMC system. That is, no matter how precise the sensors may be, a sizable portion of the surrounding terrain will be obscured from view and must therefore be tentatively labeled hazardous. Step distances will then be limited, not by basic sensor capabilities as assumed in Section 9, but by the maximum distances at which knowledge of the terrain can be obtained with any sensor.

The degree to which this might affect mission performance under different modes of operation was not analyzed in this study. However, it would seem to be considerable, and it should be subjected to analysis. Such analysis might involve statistical modeling of the terrain and Monte Carlo simulation of actual traverses.

Another potentially fruitful area for further analysis is in the development of optimal strategies for control. Quite likely, in any level of automatic control the strategy will be quite a significant determinant of overall mission performance. If this strategy is to be preprogrammed in either a deterministic or an adaptive manner, one also needs to define the criteria which lead to the choice of strategy as situations change. The potential for the application of adaptive, learning, and/or self-organizing approaches should be examined more thoroughly, especially with regard to the semiautomatic and fully automatic on-board data processing software.

The subject of navigation was barely touched upon in this study. However, for many types of missions it will be of great importance to have navigational data. Future analytical effort should include a thorough study of the techniques of long distance navigation on the moon and planets to evolve methods which are capable of meeting a broad spectrum of requirements, including the problem of correlating orbiter-derived data with data obtained from vehicle sensors.

Much more detailed mission analysis is required before a detailed mechanization can be recommended. To some extent such analysis may depend upon more specific definitions of missions. The analysis should take into account the times required to perform purely scientific tasks and the associated power and weight requirements. It should also examine the relationship between scientific requirements and motion control requirements from the standpoint of common use of certain instruments, especially imaging sensors.

The impact of the desirability for common approaches to the lunar and planetary RVMC problems should be studied to determine the effects of off-optimum operation in the one case to accommodate the other. Also, for a concept capable of "optimal" operation in both cases, the extent of disuse of equipment in either case should be evaluated.

For purposes of mechanization, it will be necessary to enumerate in more detailed fashion the salient characteristics of various sensors. For semiautomatic operation it seems especially important to investigate nonimaging sensors that are amenable to automatic appraisal and decision processes.

The relative balance between basic mobility and control sophistication is a highly complex subject that was merely alluded to on the present study, but which deserves careful consideration. It involves not only weight trade-offs, but cost and reliability as well, and should consider the general flexibility to perform a variety of functions over a range of environments.

In the trade-off analyses of Section 9, it was necessary to make a number of assumptions regarding the times required to perform certain functions. Most notable among these were the times required for ground data processing and for antenna pointing. Both of these constituted significant portions of the overall operational cycle and need to be examined much more closely. In the case of ground data processing this involves more detailed definition of the overall system mechanization, including the space-based equipment.

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